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To: Dr. D. Mills
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HOURLY FORECAST MODELS FOR THE LAKE ERIE ELEVATIONS

F. Camacho
Mathematician
Reliability & Statistics Section
Operations Research Department

ABSTRACT

An attempt to develop a statistical forecasting model to predict the hourly elevations of Lake Erie at Fort Erie for a period of six hours ahead was carried out. A model is considered acceptable if: (i) it improves forecastability as compared to the existing model; and (ii) it forecasts four out of five times surge and immersion conditions within a range of 30 cm (1 ft), two hours ahead of time, and within 60 cm (2 ft), four hours ahead of time. Given the constraints of time and resources, it was impossible to carry out an exhaustive study of all the empirical models and only some of the models that have been proposed in the literature for the forecasting of geological series were considered. These included the families of autoregressive-moving (ARMA) models and nonparametric models including both univariate and multivariate versions. Unfortunately, none of the models included in the study met the user's requirements. Further research is needed to find an adequate empirical model.

job	file	date	report no.
72-138-000	809.7	November 24, 1989	89-239-K

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To Mr. D. Mills
Director of Research

1. INTRODUCTION

This report presents the work carried out by the Reliability & Statistics Section of the Operations Research Department in response to a request by Mr. I. Corbu of the Operations Planning Facilities Department. The objective of the work was to develop a statistical forecasting model to predict hourly Lake Erie elevations at Fort Erie, for a period of six-hours ahead and based only on historical information. The Lake Erie elevation forecasts are required as an input for obtaining forecast values for the Niagara River flows which are used by Ontario Hydro and the New York Power Authority.

Under normal conditions, Lake Erie is relatively calm. However, under abnormal conditions Lake Erie is subject to meteorological events that produce oscillations on the surface which alter the elevation of the lake at Fort Erie. In many instances, these oscillations can induce changes in the elevation in excess of one meter (several ft). On average, a change of 30 cm (1 ft) on the elevation of the lake at Fort Erie is translated into a change of 540 cms (20,000 cfs) on the flows of the Niagara River. This is a large amount of water that could be properly utilized if it were possible to predict its availability.

Currently, Ontario Hydro uses a one-dimensional forecasting model for the Lake Erie elevations that is based on a simulation of the dynamics of the lake and that requires, as input, values of the predicted wind velocities and wind directions. The forecastability of the model is limited by the accuracy of the wind forecasts and unless these can be improved, the model can not be enhanced. The analysis of empirical forecasting models was considered a potential avenue for finding improvements in the forecast values.

A forecasting model will be considered acceptable if it is able to: (i) improve our the forecastability of the existing model; and (ii) forecast four out of five times surges and immersion conditions within a range of 30 cm (1 ft) two hours ahead of time, and within 60 cm (2 ft) four hours ahead of time.

The following section presents a description of the data that were used in the study together with the results of the descriptive statistical analyses that were carried out. Section 3 briefly describes the models that were used in this study. Section 4 presents the results. Finally, Section 5 presents the conclusions.

2. DATA ANALYSIS

The data used for the development of the forecasting model consisted of (i) the hourly Lake Erie elevations at Fort Erie from 1966 to 1988; and (ii) hourly information of wind speed and wind direction. The wind information was available from four inland weather stations (Buffalo, Simcoe, Cleveland, and Toledo) and one automated station located in the middle of the lake (Long Point). The information from the inland weather stations was reduced to the hourly

average of the wind speed along the direction of the axis of the lake and covered the period from 1966 to 1979. The wind information at Long Point was converted to the wind speed component along the direction of the axis of the lake and was restricted to the period from 1966 to 1988. It should be pointed out that additional meteorological data consisting of atmospheric pressure and air temperature, as well as data from other stations were also available, but were not used in this study.

2.1 Analysis of Elevation Surges

An initial analysis of the elevation data was carried out to identify the events when the elevation of the lake lied outside the interval determined by the monthly median plus or minus 15 cm 0.5 ft. Elevation levels larger than the upper limit of the interval were called type 1 surges, and elevation levels smaller than the lower limit of the interval were called type 2 surges. The following statistics were calculated for each of these types of surges. The results are given in Appendix 1.

- The number of surge events in a month for each year.
- The proportion of surges in a month by duration of the surge (1 hour, 2 hours, ... , and 7 or more hours).
- The maximum, minimum, mean, and standard deviation of the surge intensity by duration of the surge.
- The distribution of the number of surges by range intensity (in increments of 15 cm ie, 0.5 ft).
- Histograms of the distribution of the duration and intensity of the surges.

2.2 Wind Analysis

An analysis of surge events for the component of the wind speed along the axis of the lake was carried out. Wind speed values larger than the monthly medians plus 8 km/h were considered type 1 surges, and values smaller than the monthly medians minus 8 km/h were considered type 2 surges. Similar statistics to those calculated for the elevation surges were obtained. The results are given in Appendix 2.

2.3 Association Between Elevation Surges and Wind Values

To investigate the possibility of developing a forecasting model that could predict elevation surge events using only wind information, an analysis of the characteristics of the wind values that occur prior to different surge events was carried out. The analysis concentrated in determining if the *historical* wind values could be used to discriminate among calm water levels, type 1 surges and type 2 surges. Wind values would discriminate if the range of values occurring prior to each one of the three events are different.

To do the analysis the following procedure was used.

1. For each time t and for a given lag value of period L and a number k , the sum of k wind values were calculated as $s_t = w_{t-L} + \dots + w_{t-L-k+1}$.

2. The value s_t was classified as E0, E1, or E2 if the event at time $t+1$ was calm water, type 1 surge or type 2 surge, respectively.
3. The range of values for E0, E1 and E2 were calculated.

Figure 1 presents a plot of the range of values for the month of November from 1969 to 1984 with $k=5$ and $L=0$. The range of values is indicated by a horizontal line with the letters L (smallest value), Q (lower and upper quartile), M (median) and H (largest value). The column NP indicates the number of observations in the particular group of values. It can be observed that with the exception of very few cases, in 1970 and 1974 the range of values that occurred prior to a positive surge, a negative surge, or during calm waters was the same. The same general result was observed for other months and for other values of k and L . However, it should be pointed out that when the value of L is negative (i.e., when the value of s_t includes the value of w_{t+1}) some discrimination between E1 and E2 can be observed, but not between E0 and the two types of surges. These results indicate that *historical* wind values *alone* do not discriminate among surge events. Therefore, it is not possible to develop a forecasting model that could predict elevation surge events using wind information as the only predictor.

3. FORECASTING MODELS

Univariate and multivariate forecasting models were considered in the study. The univariate models made use of only the historical information of the lake elevations to develop the model. The multivariate models made use of more variables. The univariate models considered in the study were the family of autoregressive moving average (ARMA) models/1/, and the family of nonparametric models/2,3/. The multivariate models included only the family of multivariate nonparametric models. The following sections provide a simple description of the models.

3.1 Autoregressive Moving Average (ARMA) Models

The autoregressive-moving average (ARMA) model of order (p,q) assumes that the current observation, y_t , is related (in a linear manner) to the p most current observations $y_{t-1}, \dots, y_{t-p}$, to a unknown random innovation (or noise), a_t , and to the q most current innovations $a_{t-1}, \dots, a_{t-q}$. By writing $w_t = (y_t - \mu)$, where μ is the mean of the series, the model for y_t can be expressed as

$$w_t = \phi_1 w_{t-1} + \phi_2 w_{t-2} + \dots + \phi_p w_{t-p} + a_t + \theta_1 a_{t-1} + \theta_2 a_{t-2} + \dots + \theta_q a_{t-q}.$$

The coefficients ϕ_i , $i=1, \dots, p$, are called the autoregressive (AR) parameters and they represent the weights given to previous observations. The values θ_j , $j=1, \dots, q$, are called the moving average (MA) parameters and they represent the weights given to previous innovations. It is assumed that the innovations a_t , $t=1, 2, \dots$ are uncorrelated random variables with mean zero and variance σ^2 , and usually, normally distributed. Since the model assumes that the set of innovations follow a parametric distribution function (ie., normal), the model is said to be *parametric*.

Given a time series data set, special algorithms are used to identify the order of the model (the values for p and q) and to estimate the values of the parameters. Once the parameters are estimated, sufficient analyses need to be made to ensure that the selected model fit the data reasonably well. After an adequate model is selected, the forecasts are calculated iteratively. In the calculation of the forecasts, future values of the innovations are set to zero, and past values are set to the difference between the observed and the fitted (or predicted) values.

A basic assumption for the validity of the ARMA model is the *stationarity* condition (ie., it is required that the data set be homogeneous which implies that the characteristic of the series can not change over time). Intuitively, however, it can be appreciated that this assumption is violated by the hourly Lake Erie elevations, since the conditions of the lake during surge events are not the same as the characteristics of the lake at other times (ie., the data set are not homogeneous). In this situation, the ARMA model can not predict surge events since there is no information about them in the immediate past observations (they belong to a different type of events).

3.2. Nonparametric Models

Nonparametric models use statistical techniques that allow the estimation of the distribution function of a series without the prior assumption of a particular family of parametric distributions as is the case in the ARMA models (ie., without assuming that the series follow a normal, or a lognormal or any other type of parametric distribution).

Two other ideas are involved in the nonparametric model: the idea of a *Markov process* and the idea of *continuity*. A time series y_t is said to be a Markov process if the conditional distribution of y_{t+1} given the set of historical values or states $\{y_j, j=1, \dots, t\}$ is the same as the conditional distribution of y_{t+1} given $\{y_t\}$ (ie., if the future value depends only on the most recent state). Note that the Lake Erie elevations may not have the strict Markov property, but it can be approximated by taking the vectors of the most recent observations as the state. The Markov process is fully characterized by giving the transition probability density function (pdf) $f(y_{t+1}|x_t)$, where y_{t+1} represents elevation at time $t+1$ and x_t represents the state at time t (ie., by specifying the possible values of the next hour elevation, y_{t+1} , together with their respective frequencies, given that the value of the current state is x_t). *Continuity* assumes that $f(y|x)$ is continuous in x , ie., that if $\underline{x}$ is near x , then $f(y|\underline{x}) \approx f(y|x)$.

To see how the previous ideas are brought together, assume that the data $y_k, k=1, \dots, t$ represent the historical Lake Erie elevations and that the objective is to estimate y_{t+1} . Furthermore, assume that the lake elevations can be represented by a Markov process whose state x_t is the vector of the last d observations, ie. $x_t = (y_t, y_{t-1}, \dots, y_{t-d+1})$. The optimum forecast for y_{t+1} is the expected value of the possible transitions from x_t . If we could have a set of independent observations of such transitions, the forecast could be estimated as the simple average of those values. This set could be obtained by searching the data base for the cases where $x_k = x_t$, and selecting the value y_{k+1} as a member of the set. Unfortunately, even if the data set is large, this set may be empty. However, using the idea of *continuity*, we could enlarge the number of observations in the set by including all the y_{k+1} values for which $x_k \approx x_t$ (ie., $y_{t-i} \approx y_{k-i}$ for $i=0, \dots, d-1$). In this case a weighted average would be recommended for estimating y_{t+1} , where y_{k+1} would be weighted by a factor that takes into account the distance from x_k to x_t , ie.,

$$y_{t|1} = \sum w_k y_{k+1}$$

where $w_k = g(x_t - x_k), k=1, \dots, t-1$, represent the weights and $g(\cdot)$ is a function that measures the distance between x_t and x_k and the sum is over all the values of historical information. More general, for estimating y_{t+r} (ie., the r -step ahead prediction), the following weighted sum is used:

$$y_{t|r} = \sum w_k y_{k+r}$$

3.2.1 Univariate Model

The univariate nonparametric model defines the state of the system as the vector of the last d Lake Erie elevations, ie., $x_t = (y_t, y_{t-1}, \dots, y_{t-d+1})$. The values of d is called the memory of the system.

3.2.2 Multivariate Model

The multivariate nonparametric model defines the state of the system based on two variables: the historical lake elevations and the historical wind values. Two alternative models could be developed: one using the wind "profile" and the other using the wind "strength". When the wind "profile" is used, the state of the model is defined as the vector of the last ds Lake Erie elevations together with the vector of last dw wind values in the direction of the axes of Lake Erie, ie. $x_t = (y_t, y_{t-1}, \dots, y_{t-ds+1}, wd_t, wd_{t-1}, \dots, wd_{t-dw+1})$ where wd_t represents the wind values. When the wind "strength" is used, the state is defined as the vector of the last ds Lake Erie elevations together with the sum of last dw wind values in the direction of the axes of Lake Erie, ie. $x_t = (y_t, y_{t-1}, \dots, y_{t-ds+1}, sw_t)$ where $sw_t = wd_t + wd_{t-1} + \dots + wd_{t-dw+1}$. In both cases, the values of ds and dw are called the memories of the system. Note that if $dw = 0$, the model is equivalent to the univariate model.

4. RESULTS

4.1 ARMA Model

As mentioned in Section 3.1, it is necessary to carry out specific analysis to identify and estimate an adequate ARMA model. This work was attempted for the Lake Erie elevations from the period October 1, 1985, to November 30, 1985. The McLeod-Hipel Time Series Package/4/ was used to carry out the calculations. Unfortunately, it was not possible to find a model that would pass all the diagnostic procedures, even when a large number of parameters was used to fit the model. The main difficulty was that the stationarity assumption was violated by the data. Notice that one of the main assumptions of the ARMA model is that all the innovations follow a normal distribution with constant parameters over time. However, it is obvious that the innovations associated with surge events follow a different distribution than those associated with calm water.

Even though it was not possible to fit an adequate model and the basic assumptions of the model were violated by the data, an attempt was made to use one of the fitted models to calculate the forecasts from December 1, 1985, to December 31, 1985. This period contains three type 1 surges and two type 2 surges. Figure 2 provides a plot of the one step ahead forecasts errors (the forecast error is defined as the difference between the observed elevation value and the forecast value). It can be noted that most of the forecast errors are within the ± 30 cm (± 1 ft) interval. The ones lying outside the interval correspond to the type 1 surge events. This plot illustrates the expected performance of the ARMA model in forecasting the hourly Lake Erie elevations: during periods of calm water the model is expected to perform relatively well; however, the model can not adequately predict surge events.

4.2 Nonparametric Models

Both, univariate and multivariate nonparametric models were used to calculate the forecasts of the Lake Erie elevations. A computer program was developed to carry out the calculations. The program allows the user to specify the order of the state vector for the model (ie. the values of ds

and dw) and whether the wind "profile" or "strength" should be used in the model. By specifying the memory value for wind as zero (ie. $dw=0$), the program can be used to obtain univariate non-parametric models.

Table 1 lists the time periods that were used to calculate the forecasts. Additional test periods during 1985 and 1987 had been selected, but unfortunately, there were too many missing values on the wind data set and that it was impossible to develop the nonparametric model for those cases. For each one of the test periods, six-step ahead forecasts were obtained for a total of 60 hours starting at the first hour of the given date. To control for seasonal effects, the model used 60 days of historical data (1440 hours) starting 13 months (one year and one month) prior to the beginning of the forecast period. To control for the possible changes in the elevation of the lake from one year to the next, the historical elevation values were adjusted so that at each time the medians of the elevation values of the two state vectors being compared were the same.

In the following cases it was not possible to obtain adequate forecast values.

- (i) One of the entries on the state vector was missing (ie, one of $y_{t-1}, \dots, y_{t-ds+1}, wd_t, wd_{t-1}, \dots, wd_{t-dw+1}$ was missing). In this case the state vector could not be determined.
- (ii) There were not enough observations in the data base with a state value in the neighborhood of the current state x_t .

Several values of ds and dw were used to obtain different models. Tables 2 and 3 present the results for the following memory values:

Table 2: memory surges = 5, memory wind = 0 (univariate)

Table 3: memory surges = 5, memory wind = 3.

For each test period, the forecast errors (FE) $e_{r|t} = y_{t+r} - y_{r|t}$ were calculated for $r = 1, 2, \dots, 6$ and $t = 1, \dots, 60$. For each r , the r -step ahead mean absolute forecast error (MAFE) was calculated as:

$$MAFE = \sum |e_{r|t}| / n$$

where the value of n is the effective number of observations for the corresponding step ahead forecast error. The MAFE was calculated independently for the following cases.

- (i) The hours in the period when no surge was identified (ie, if the elevation is within 15 cm, ie. 0.5 ft of the monthly median).
- (ii) The hours in the period where a surge was identified.
- (iii) All the hours in the period.

It can be seen from the Tables that the multivariate model is not much better than the univariate. In addition, the performance of the model depends on the period being forecasted.

To analyze if the forecast models meet the user's requirements, it is necessary to study with more detail the forecast errors. This can be done with the help of the plots of the 2-step and 4-step ahead forecast errors. These plots are given in the figures of Appendix 3. Each figure presents a plot of the forecast errors together with reference lines at ± 30 cm (1 ft) (for 2-step ahead) or ± 60

cm (2 ft) (for 4-step ahead) for those hours associated with a surge. Each surge event is identified by a separate block. A forecast period may have more than one surge. For example, the forecast period dated 17 April 1969 has three surge events.

To determine if a model meets the user's requirements in a given surge event, it is sufficient to check that the plot of the forecast errors does not fall outside the reference lines. The proportion of surge events that are forecasted within the user's requirements is estimated by the ratio of the number of surge events where the model meets the user's requirements and the total number of surge events. For the 2-step ahead forecasts, this estimate is $29/43 = 0.674$ and for the 4-step ahead forecasts, the estimate is $34/43 = 0.791$. Note that these estimates depend on the number of surge events. This number changes when one combines adjacent surge events into single ones, an alternative that seems quite natural. In this case the estimates change only marginally. They are: for 2-step ahead = $25/37 = 0.676$ and for 4-step ahead = $30/37 = 0.881$. The above results imply that the models do not forecast surge events according with the user's requirements.

5. CONCLUSIONS

Several empirical forecasting models were considered in this study for forecasting Lake Erie elevations. Among the family of parametric models, the subclass of ARMA models was considered. This subclass is quite rich, and has been proposed by several authors for the forecasting of geological time series. It includes the popular exponential smoothing methods. Unfortunately, it was found that, because of surge events, the hourly elevations do not meet the assumptions of stationarity required by the ARMA models, and therefore, it was not possible to fit adequate models to the data.

The other class of models considered in the study was the class of nonparametric models. These models have the advantage that they could be used under more general assumptions than the ARMA models. These models have also been suggested for applications on the flood-warning problem (see/3/). Two basic approaches were considered. One was the development of a model that used wind speed along the axis of the lake for the prediction of surges events. Unfortunately, as shown in Section 2.3, it was not possible to develop such a model since the historical wind information do not discriminate between calm water and surge events. The other was to use univariate and multivariate models to forecast the lake elevations directly. Several models were considered using different values of elevation and wind memories and using different types of state vectors.

No more models could be tested because of the time and resource limitations. The results of Section 4.2 indicate that none of the models above meets the user requirements. Further work is needed to find an adequate empirical forecasting model. This work will be of a research nature and may not promise the desired results.

It is unfortunate that the work carried out in this study did not result in a model that could meet the user's requirements even though the study only considers models that had been proposed in the literature for the forecasting of geological series. There are several reasons that could explain this outcome and two of these deserve special mention. One is that other meteorological variables such as atmospheric pressure and air or water temperature gradient at the surface of the lake may help in determining a surge event, but these variables were not considered in the analysis. The other is that the elapse time between the occurrence of a certain wind condition and the occurrence of a surge is only a fraction of an hour, so that it may not be possible to determine surge events one hour ahead. If this is the situation, it may be almost impossible to develop adequate empirical models for the forecasting of the Lake Erie elevations.

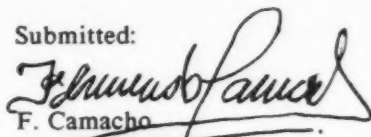
One additional observation needs to be made about the scope of this study. It is the fact that no attempt was made to compare the models developed here with the existing model. It is not known how far the existing model is from meeting the user's requirements and how the model would perform in a forecasting competition. This analysis is required in order to give a more complete assessment of the models developed here. However, this work was outside the scope of the study.

Approved:



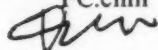
A.H. Chung
Manager
Operations Research Dept

Submitted:



F. Camacho
~~Mathematician~~
Reliability and Statistics Section

FC:cmh



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FIGURE 1

Correlation wind with surges.
Points = 5. Lag = 0. Large Surges

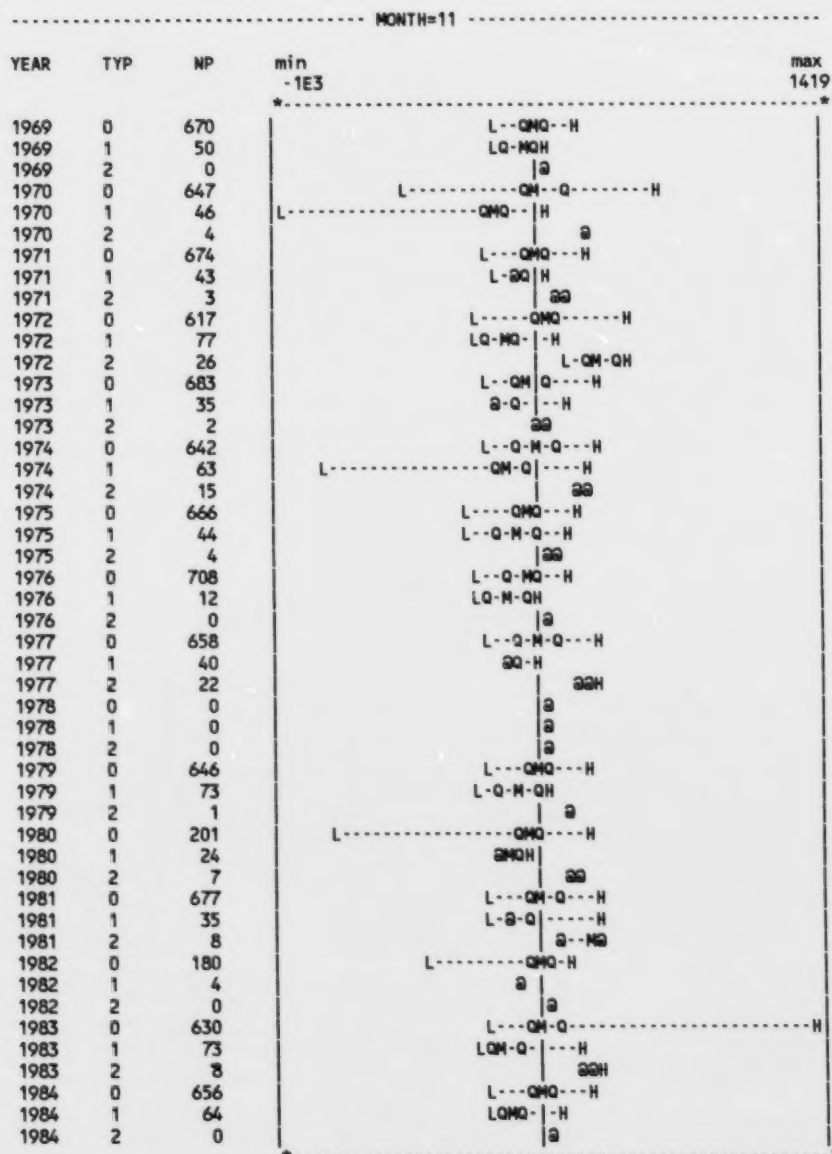


FIGURE 2

ARMA FORECAST

1-step ahead forecast errors

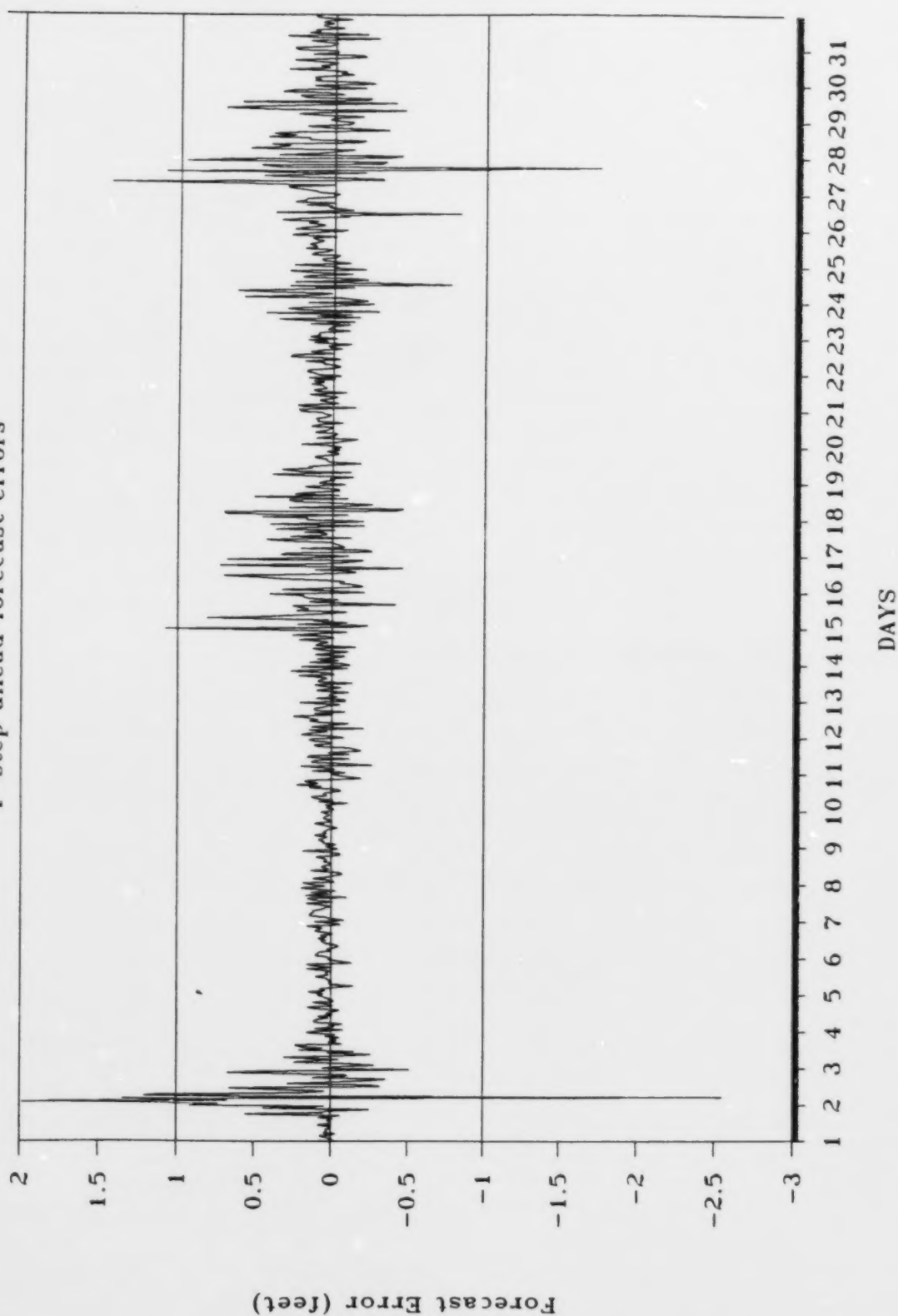


TABLE 1

Time Periods for Testing the Nonparametric Model

TEST CASE	TIME PERIOD	SURGE TYPE
1	APRIL 17/69	-
2	MAY 8/69	+
3	SEPTEMBER 23/69	+ / -
4	APRIL 20/70	+
5	DECEMBER 3/70	+ / -
6	OCTOBER 19/71	CALM
7	NOVEMBER 6/71	+
8	DECEMBER 14/71	+
9	JUNE 10/79	+
10	AUGUST 9/79	+
11	NOVEMBER 25/79	+

TABLE 2

Mean Absolute Forecast Error for
the Univariate Nonparametric Model (in ft) Memory: Surges=5 Wind=0

DATE	SURGE	N	1-STEP	2-STEP	3-STEP	4-STEP	5-STEP	6-STEP
17 APR 1969	NO SURGE	32	0.11	0.17	0.17	0.19	0.26	0.28
	SURGE	34	0.29	0.41	0.44	0.50	0.57	0.66
	ALL	66	0.21	0.30	0.32	0.37	0.43	0.50
8 MAY 1969	NO SURGE	45	0.23	0.34	0.43	0.51	0.55	0.56
	SURGE	21	0.51	0.86	1.16	1.32	1.57	1.78
	ALL	66	0.31	0.48	0.65	0.76	0.89	0.97
23 SEP 1969	NO SURGE	59	0.10	0.16	0.22	0.26	0.26	0.25
	SURGE	7	0.12	0.27	0.39	0.46	0.59	0.70
	ALL	66	0.10	0.18	0.24	0.28	0.30	0.30
20 APR 1970	NO SURGE	42	0.28	0.40	0.48	0.54	0.60	0.58
	SURGE	24	0.33	0.60	0.75	0.91	1.11	1.33
	ALL	66	0.30	0.48	0.59	0.68	0.78	0.85
3 DEC 1970	NO SURGE	27	0.21	0.39	0.50	0.61	0.64	0.61
	SURGE	39	0.42	0.71	0.99	1.16	1.36	1.56
	ALL	66	0.33	0.57	0.79	0.95	1.09	1.21
19 OCT 1971	NO SURGE	66	0.06	0.09	0.12	0.13	0.15	0.15
	ALL	66	0.06	0.09	0.12	0.13	0.15	0.15
6 NOV 1971	NO SURGE	22	0.15	0.30	0.38	0.46	0.55	0.71
	SURGE	44	0.19	0.32	0.43	0.51	0.57	0.60
	ALL	66	0.18	0.31	0.41	0.50	0.56	0.63
14 DEC 1971	NO SURGE	31	0.17	0.30	0.44	0.57	0.71	0.78
	SURGE	35	0.38	0.62	0.82	1.02	1.13	1.26
	ALL	66	0.27	0.46	0.64	0.82	0.94	1.05
10 JUN 1979	NO SURGE	54	0.12	0.16	0.19	0.21	0.26	0.26
	SURGE	12	0.36	0.58	0.70	0.87	0.99	1.07
	ALL	66	0.16	0.25	0.29	0.34	0.40	0.42
9 AUG 1979	NO SURGE	53	0.15	0.25	0.33	0.41	0.48	0.52
	SURGE	13	0.25	0.47	0.65	0.80	0.93	1.04
	ALL	66	0.18	0.30	0.40	0.49	0.58	0.63
25 NOV 1979	NO SURGE	33	0.18	0.22	0.32	0.45	0.57	0.62
	SURGE	33	0.29	0.49	0.58	0.63	0.71	0.79
	ALL	66	0.24	0.36	0.46	0.55	0.65	0.72
AVERAGE	NO SURGE	464	0.15	0.24	0.30	0.36	0.41	0.43
	SURGE	262	0.32	0.53	0.68	0.81	0.95	1.07
	ALL	726	0.21	0.34	0.45	0.53	0.62	0.68

TABLE 3

Mean Absolute Forecast Error for
the Multivariate Nonparametric Model (in ft) Memory: Surges=5 Wind=3

DATE		N	1-STEP	2-STEP	3-STEP	4-STEP	5-STEP	6-STEP
17 APR 1969	NO SURGE	32	0.12	0.18	0.19	0.21	0.27	0.28
	SURGE	34	0.29	0.40	0.44	0.50	0.57	0.66
	ALL	66	0.21	0.31	0.34	0.38	0.44	0.50
8 MAY 1969	NO SURGE	45	0.23	0.34	0.43	0.51	0.55	0.56
	SURGE	21	0.51	0.86	1.16	1.32	1.57	1.78
	ALL	66	0.31	0.48	0.65	0.76	0.89	0.97
23 SEP 1969	NO SURGE	59	0.10	0.16	0.22	0.26	0.26	0.25
	SURGE	7	0.12	0.27	0.39	0.46	0.59	0.70
	ALL	66	0.10	0.17	0.24	0.28	0.30	0.30
20 APR 1970	NO SURGE	42	0.27	0.40	0.48	0.53	0.60	0.58
	SURGE	24	0.33	0.60	0.75	0.91	1.11	1.33
	ALL	66	0.29	0.48	0.58	0.68	0.78	0.84
3 DEC 1970	NO SURGE	27	0.20	0.37	0.50	0.64	0.64	0.60
	SURGE	39	0.42	0.70	0.99	1.17	1.39	1.58
	ALL	66	0.33	0.56	0.79	0.96	1.11	1.22
19 OCT 1971	NO SURGE	66	0.06	0.09	0.12	0.13	0.15	0.15
	ALL	66	0.06	0.09	0.12	0.13	0.15	0.15
6 NOV 1971	NO SURGE	22	0.15	0.30	0.38	0.46	0.55	0.71
	SURGE	44	0.19	0.32	0.43	0.51	0.57	0.60
	ALL	66	0.18	0.31	0.41	0.50	0.56	0.63
14 DEC 1971	NO SURGE	31	0.17	0.31	0.45	0.60	0.77	0.83
	SURGE	35	0.40	0.63	0.83	1.05	1.16	1.25
	ALL	66	0.28	0.47	0.65	0.84	0.99	1.07
10 JUN 1979	NO SURGE	54	0.12	0.17	0.20	0.23	0.28	0.27
	SURGE	12	0.34	0.58	0.70	0.86	0.98	1.07
	ALL	66	0.17	0.25	0.30	0.35	0.42	0.43
9 AUG 1979	NO SURGE	53	0.15	0.24	0.32	0.40	0.47	0.52
	SURGE	13	0.24	0.46	0.64	0.80	0.92	1.00
	ALL	66	0.17	0.29	0.39	0.49	0.56	0.62
25 NOV 1979	NO SURGE	33	0.15	0.19	0.25	0.37	0.46	0.53
	SURGE	33	0.30	0.48	0.56	0.63	0.73	0.82
	ALL	66	0.23	0.34	0.42	0.51	0.61	0.69
AVERAGE	NO SURGE	464	0.15	0.23	0.30	0.36	0.41	0.43
	SURGE	262	0.32	0.53	0.68	0.82	0.95	1.07
	ALL	726	0.21	0.34	0.44	0.53	0.62	0.68

APPENDIX 1

This Appendix presents the results of the statistical analysis of the elevation surges. As explained in Section 2.1, elevation levels larger than the monthly median plus 0.5 ft are called type 1 surges, and elevation levels smaller than the monthly median minus 0.5 ft are called type 2 surges. The following statistics are given in Tables A.1 to Table A.14.

- The number of surge events in a month for each year: Tables A1 and A2.
- The proportion of surges in a month by duration of the surge (1 hour, 2 hours, ... and 7 or more hours), together with the maximum, minimum, mean, and standard deviation of the surge intensity: Tables A3 to A10.
- The distribution of the number of surges by range intensity (in increments of 15 cm (0.5 ft)): Tables A11 and A12.
- Histograms of the distribution of the duration and intensity of the surges: Tables A13 and A14.

TABLE A1

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

surge type 1

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	NOV	DEC	ALL
	N	N	N	N	N	N	N	N	N	N	N	N
YEAR												
1966	15	8	23	14	14	5	18	16	19	21	16	169
1967	26	21	7	14	16	13	5	10	14	30	23	179
1968	12	17	6	15	17	16	5	10	15	14	18	145
1969	15	8	11	21	12	12	12	11	13	14	20	169
1970	16	7	12	15	10	8	19	10	17	15	31	160
1971	20	15	18	11	11	11	11	9	6	19	23	154
1972	20	11	17	18	4	4	14	8	13	12	22	143
1973	19	11	19	17	16	6	12	9	15	15	16	155
1974	29	6	21	16	20	10	17	20	11	16	21	187
1975	23	20	20	8	7	20	11	12	13	21	11	166
1976	17	24	17	13	19	11	14	6	16	21	32	190
1977	1	8	24	8	9	12	11	27	22	3	16	141
1978	10	0	9	12	5	8	7	17	13	18	24	123
1979	16	5	17	16	3	7	7	21	9	15	20	136
1980	19	12	12	14	12	16	10	19	27	20	24	185
1981	13	17	9	25	2	14	7	14	13	15	18	147
1982	21	3	19	11	1	10	8	15	17	21	20	146
1983	16	9	11	17	17	2	14	14	20	18	18	156
1984	10	13	13	9	21	10	9	6	12	15	26	144
1985	15	12	12	14	9	20	15	11	13	17	19	157
1986	17	9	9	11	9	17	3	30	16	17	20	158
1987	21	13	8	15	6	25	4	11	7	28	17	155
ALL	371	249	314	314	240	257	233	306	321	385	455	3445

TABLE A2

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

surge type 2

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	NOV	DEC	ALL
	N	N	N	N	N	N	N	N	N	N	N	N
YEAR												
1966	9	3	13	8	6	3	4	3	9	5	18	81
1967	15	13	6	9	11	6	0	9	12	19	22	122
1968	11	3	6	3	9	12	5	7	1	12	21	90
1969	7	4	3	14	15	2	13	5	6	8	14	91
1970	1	2	11	15	7	10	2	6	10	16	20	100
1971	13	11	9	5	2	4	5	8	11	16	23	107
1972	22	3	9	13	8	3	1	8	11	12	18	108
1973	14	7	20	8	2	5	12	5	18	22	12	125
1974	17	11	18	9	12	6	6	1	12	13	5	110
1975	23	10	9	3	2	7	3	8	7	12	13	97
1976	15	14	17	6	3	10	5	6	7	16	17	116
1977	0	6	8	7	11	4	4	2	10	4	8	64
1978	12	0	2	10	4	3	5	4	10	11	26	87
1979	16	3	15	20	6	2	0	3	9	10	20	104
1980	10	4	9	12	4	5	1	1	14	13	14	87
1981	0	2	3	6	3	4	3	9	15	10	6	61
1982	9	4	27	10	5	5	3	11	3	18	10	105
1983	10	5	10	19	6	5	6	6	10	9	17	103
1984	3	1	14	12	8	1	3	6	6	9	12	75
1985	23	5	11	5	4	9	7	6	7	16	22	115
1986	5	7	9	13	9	10	1	12	12	13	9	100
1987	10	8	7	9	5	3	4	10	6	10	14	86
ALL	245	126	236	216	142	119	93	136	206	274	341	2134

TABLE A3

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

DURATION 1
AND SURGE TYPE 1

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	89	7.91	0.51	0.60	1.17	0.12
FEB	53	4.71	0.51	0.57	0.94	0.08
MAR	85	7.56	0.51	0.60	1.13	0.12
APR	113	10.04	0.51	0.61	1.80	0.17
MAY	101	8.98	0.51	0.63	1.41	0.15
JUN	122	10.84	0.51	0.65	1.50	0.18
JUL	126	11.20	0.51	0.63	1.73	0.16
AUG	134	11.91	0.51	0.64	1.31	0.14
SEP	119	10.58	0.51	0.61	1.06	0.13
NOV	82	7.29	0.51	0.61	2.06	0.20
DEC	101	8.98	0.51	0.58	1.14	0.09
ALL	1125	100.0	0.51	0.62	2.06	0.15

DURATION 1
AND SURGE TYPE 2

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	76	9.62	-1.30	-0.56	-0.51	0.11
FEB	40	5.06	-1.29	-0.58	-0.51	0.13
MAR	88	11.14	-1.07	-0.57	-0.51	0.09
APR	80	10.13	-1.22	-0.59	-0.51	0.12
MAY	72	9.11	-1.00	-0.58	-0.51	0.09
JUN	59	7.47	-1.65	-0.62	-0.51	0.19
JUL	43	5.44	-2.42	-0.68	-0.51	0.41
AUG	55	6.96	-1.46	-0.62	-0.51	0.20
SEP	68	8.61	-1.17	-0.58	-0.51	0.10
NOV	95	12.03	-0.89	-0.56	-0.51	0.05
DEC	114	14.43	-0.80	-0.56	-0.51	0.05
ALL	790	100.0	-2.42	-0.58	-0.51	0.15

TABLE A4

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)

Based on monthly medians +/- 0.5 feet

DURATION 2
AND SURGE TYPE 1

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	49	7.77	0.51	0.65	1.13	0.12
FEB	45	7.13	0.51	0.70	1.12	0.13
MAR	59	9.35	0.51	0.69	1.40	0.18
APR	54	8.56	0.52	0.72	1.33	0.19
MAY	61	9.67	0.51	0.67	1.01	0.12
JUN	61	9.67	0.51	0.76	1.58	0.23
JUL	44	6.97	0.52	0.74	1.27	0.18
AUG	71	11.25	0.51	0.77	1.99	0.26
SEP	54	8.56	0.51	0.71	1.36	0.19
NOV	64	10.14	0.51	0.68	1.05	0.12
DEC	69	10.94	0.53	0.68	1.53	0.17
ALL	631	100.0	0.51	0.71	1.99	0.18

DURATION 2
AND SURGE TYPE 2

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	37	11.01	-1.50	-0.63	-0.52	0.17
FEB	18	5.36	-0.91	-0.61	-0.52	0.10
MAR	28	8.33	-0.90	-0.64	-0.52	0.10
APR	33	9.82	-1.05	-0.63	-0.51	0.11
MAY	24	7.14	-1.04	-0.65	-0.51	0.14
JUN	19	5.65	-1.47	-0.64	-0.52	0.22
JUL	14	4.17	-0.97	-0.63	-0.53	0.12
AUG	23	6.85	-1.07	-0.63	-0.52	0.14
SEP	33	9.82	-0.78	-0.61	-0.51	0.07
NOV	46	13.69	-0.86	-0.61	-0.51	0.08
DEC	61	18.15	-1.03	-0.63	-0.53	0.10
ALL	336	100.0	-1.50	-0.63	-0.51	0.12

TABLE A5

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

DURATION 3
AND SURGE TYPE 1

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	23	8.13	0.55	0.70	1.00	0.10
FEB	22	7.77	0.54	0.70	1.13	0.17
MAR	28	9.89	0.55	0.71	1.23	0.15
APR	24	8.48	0.55	0.79	1.96	0.29
MAY	24	8.48	0.53	0.75	1.31	0.19
JUN	20	7.07	0.60	0.91	1.42	0.27
JUL	17	6.01	0.58	0.84	1.36	0.26
AUG	39	13.78	0.53	0.83	2.89	0.41
SEP	28	9.89	0.57	0.77	1.34	0.22
NOV	26	9.19	0.58	0.80	1.53	0.23
DEC	32	11.31	0.54	0.85	1.77	0.29
ALL	283	100.0	0.53	0.79	2.89	0.26

DURATION 3
AND SURGE TYPE 2

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	24	11.76	-1.04	-0.72	-0.56	0.14
FEB	10	4.90	-0.90	-0.71	-0.58	0.11
MAR	19	9.31	-1.03	-0.68	-0.55	0.13
APR	20	9.80	-1.10	-0.69	-0.53	0.15
MAY	11	5.39	-0.96	-0.73	-0.54	0.14
JUN	14	6.86	-1.35	-0.76	-0.54	0.28
JUL	14	6.86	-0.81	-0.64	-0.52	0.08
AUG	12	5.88	-0.86	-0.64	-0.56	0.08
SEP	20	9.80	-1.27	-0.69	-0.55	0.17
NOV	30	14.71	-1.24	-0.69	-0.56	0.15
DEC	30	14.71	-0.93	-0.68	-0.56	0.10
ALL	204	100.0	-1.35	-0.69	-0.52	0.14

TABLE A6

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

DURATION 4
AND SURGE TYPE 1

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	21	11.93	0.60	0.84	1.59	0.26
FEB	12	6.82	0.60	0.77	1.24	0.19
MAR	12	6.82	0.52	0.76	1.26	0.22
APR	22	12.50	0.56	0.79	1.24	0.18
MAY	14	7.95	0.55	0.80	1.09	0.18
JUN	10	5.68	0.56	0.93	1.82	0.38
JUL	15	8.52	0.53	0.80	1.37	0.19
AUG	13	7.39	0.56	0.87	1.50	0.33
SEP	15	8.52	0.58	0.78	1.37	0.22
NOV	23	13.07	0.58	0.89	1.87	0.32
DEC	19	10.80	0.56	0.78	1.14	0.18
ALL	176	100.0	0.52	0.82	1.87	0.24

DURATION 4
AND SURGE TYPE 2

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	20	14.60	-1.13	-0.69	-0.52	0.16
FEB	6	4.38	-0.82	-0.62	-0.57	0.10
MAR	14	10.22	-0.93	-0.67	-0.54	0.11
APR	11	8.03	-0.81	-0.67	-0.57	0.07
MAY	12	8.76	-0.77	-0.64	-0.56	0.07
JUN	3	2.19	-1.02	-0.82	-0.65	0.19
JUL	6	4.38	-0.80	-0.70	-0.67	0.05
AUG	15	10.95	-0.94	-0.70	-0.55	0.11
SEP	23	16.79	-1.46	-0.73	-0.57	0.22
NOV	10	7.30	-0.76	-0.63	-0.53	0.07
DEC	17	12.41	-1.06	-0.69	-0.54	0.14
ALL	137	100.0	-1.46	-0.69	-0.52	0.14

TABLE A7

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

DURATION 5
AND SURGE TYPE 1

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	22	10.53	0.61	0.96	1.95	0.37
FEB	17	8.13	0.54	0.86	1.32	0.23
MAR	21	10.05	0.60	0.91	1.29	0.22
APR	21	10.05	0.61	1.06	2.04	0.37
MAY	13	6.22	0.61	0.86	1.59	0.26
JUN	17	8.13	0.58	0.94	1.75	0.36
JUL	10	4.78	0.65	0.88	1.54	0.26
AUG	21	10.05	0.68	0.95	1.45	0.23
SEP	26	12.44	0.64	0.98	2.07	0.36
NOV	18	8.61	0.57	0.83	1.06	0.14
DEC	23	11.00	0.57	1.01	2.43	0.47
ALL	209	100.0	0.54	0.94	2.43	0.32

DURATION 5
AND SURGE TYPE 2

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	13	10.74	-0.90	-0.69	-0.56	0.11
FEB	7	5.79	-0.78	-0.67	-0.58	0.07
MAR	17	14.05	-1.36	-0.78	-0.52	0.21
APR	8	6.61	-0.81	-0.70	-0.62	0.07
MAY	2	1.65	-0.68	-0.68	-0.67	0.01
JUN	5	4.13	-0.76	-0.69	-0.58	0.07
JUL	4	3.31	-0.78	-0.71	-0.67	0.05
AUG	10	8.26	-0.95	-0.72	-0.60	0.10
SEP	17	14.05	-1.28	-0.75	-0.62	0.15
NOV	17	14.05	-1.25	-0.79	-0.53	0.21
DEC	21	17.36	-1.44	-0.81	-0.57	0.25
ALL	121	100.0	-1.44	-0.75	-0.52	0.17

TABLE A8

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

DURATION 6
AND SURGE TYPE 1

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	24	12.06	0.56	1.03	2.66	0.47
FEB	21	10.55	0.62	1.21	2.35	0.50
MAR	17	8.54	0.59	1.41	3.93	1.02
APR	24	12.06	0.64	1.08	2.06	0.40
MAY	5	2.51	0.70	1.01	1.75	0.43
JUN	10	5.03	0.72	1.03	1.78	0.35
JUL	10	5.03	0.65	0.98	1.80	0.31
AUG	10	5.03	0.73	1.03	1.56	0.26
SEP	22	11.06	0.73	1.13	2.13	0.35
NOV	29	14.57	0.63	1.24	4.13	0.84
DEC	27	13.57	0.60	1.11	2.24	0.42
ALL	199	100.0	0.56	1.14	4.13	0.56

DURATION 6
AND SURGE TYPE 2

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	9	9.28	-1.45	-0.81	-0.55	0.28
FEB	7	7.22	-0.87	-0.73	-0.63	0.09
MAR	13	13.40	-1.70	-0.85	-0.58	0.28
APR	11	11.34	-1.28	-0.85	-0.60	0.19
MAY	5	5.15	-0.99	-0.79	-0.63	0.13
JUN	4	4.12	-1.03	-0.87	-0.72	0.13
JUL	5	5.15	-0.78	-0.70	-0.60	0.07
AUG	3	3.09	-0.71	-0.70	-0.67	0.02
SEP	8	8.25	-1.10	-0.82	-0.57	0.20
NOV	16	16.49	-1.42	-0.83	-0.58	0.23
DEC	16	16.49	-1.32	-0.81	-0.60	0.20
ALL	97	100.0	-1.70	-0.81	-0.55	0.20

TABLE A9

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)

Based on monthly medians +/- 0.5 feet

DURATION 7 OR MORE
AND SURGE TYPE 1

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	143	17.40	0.66	2.00	6.60	1.21
FEB	79	9.61	0.58	1.40	7.47	0.88
MAR	92	11.19	0.64	1.55	4.23	0.75
APR	56	6.81	0.60	1.64	6.71	1.15
MAY	22	2.68	0.73	1.29	3.42	0.60
JUN	17	2.07	0.78	1.31	2.39	0.52
JUL	11	1.34	0.72	1.16	1.57	0.31
AUG	18	2.19	0.65	1.20	2.67	0.48
SEP	57	6.93	0.70	1.34	3.40	0.61
NOV	143	17.40	0.72	1.97	6.41	1.07
DEC	184	22.38	0.66	1.89	6.71	1.10
ALL	822	100.0	0.58	1.73	7.47	1.03

DURATION 7 OR MORE
AND SURGE TYPE 2

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	66	14.70	-3.27	-1.21	-0.61	0.57
FEB	38	8.46	-2.99	-1.12	-0.66	0.48
MAR	57	12.69	-3.22	-1.27	-0.59	0.62
APR	53	11.80	-4.39	-1.43	-0.71	0.67
MAY	16	3.56	-2.38	-1.35	-0.83	0.42
JUN	15	3.34	-2.49	-1.09	-0.65	0.46
JUL	7	1.56	-1.30	-0.84	-0.69	0.21
AUG	18	4.01	-1.64	-0.98	-0.68	0.24
SEP	37	8.24	-2.26	-1.04	-0.58	0.34
NOV	60	13.36	-4.08	-1.27	-0.66	0.63
DEC	82	18.26	-2.51	-1.15	-0.59	0.43
ALL	449	100.0	-4.39	-1.21	-0.58	0.54

TABLE A10

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

ALL

SRGMAX

	N	PCTN	MIN	MEAN	MAX	STD
JAN	616	11.04	-3.27	0.42	6.60	1.28
FEB	375	6.72	-2.99	0.37	7.47	0.98
MAR	550	9.86	-3.22	0.22	4.23	1.04
APR	530	9.50	-4.39	0.20	6.71	1.04
MAY	382	6.85	-2.38	0.20	3.42	0.76
JUN	376	6.74	-2.49	0.31	2.39	0.76
JUL	326	5.84	-2.42	0.33	1.80	0.69
AUG	442	7.92	-1.64	0.32	2.89	0.73
SEP	527	9.45	-2.26	0.23	3.40	0.85
NOV	659	11.81	-4.08	0.39	6.41	1.24
DEC	796	14.27	-2.51	0.36	6.71	1.22
ALL	5579	100.0	-4.39	0.31	7.47	1.03

TABLE A11

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

SURGE TYPE 1

SRGMAX RANGE	DURATION							
	1			2 OR MORE			ALL	
	N	COL PCT	ROW PCT	N	COL PCT	ROW PCT	N	PCTN
0.5 - 1.0	1093	97.16	43.84	1400	60.34	56.16	2493	72.37
1.0 - 1.5	28	2.49	5.37	493	21.25	94.63	521	15.12
1.5 - 2.0	3	0.27	1.52	195	8.41	98.48	198	5.75
2.0 - 2.5	1	0.09	1.32	75	3.23	98.68	76	2.21
2.5 - 3.0	0	0	0	62	2.67	100.0	62	1.80
3.0 - 3.5	0	0	0	40	1.72	100.0	40	1.16
3.5 - 4.0	0	0	0	21	0.91	100.0	21	0.61
4.0 - 4.5	0	0	0	14	0.60	100.0	14	0.41
4.5 - 5.0	0	0	0	4	0.17	100.0	4	0.12
5.0 - 5.5	0	0	0	6	0.26	100.0	6	0.17
5.5 - 6.0	0	0	0	3	0.13	100.0	3	0.09
6.0 - 6.5	0	0	0	2	0.09	100.0	2	0.06
above 6.5	0	0	0	5	0.22	100.0	5	0.15
ALL	1125	100.0	32.66	2320	100.0	67.34	3445	100.0

SURGE TYPE 2

SRGMAX RANGE	DURATION							
	1			2 OR MORE			ALL	
	N	COL PCT	ROW PCT	N	COL PCT	ROW PCT	N	PCTN
(4.0 - 4.5)	0	0	0	2	0.15	100.0	2	0.09
(3.0 - 3.5)	0	0	0	6	0.45	100.0	6	0.28
(2.5 - 3.0)	0	0	0	7	0.52	100.0	7	0.33
(2.0 - 2.5)	2	0.25	9.52	19	1.41	90.48	21	0.98
(1.5 - 2.0)	1	0.13	1.39	71	5.28	98.61	72	3.37
(1.0 - 1.5)	16	2.03	7.44	199	14.81	92.56	215	10.07
(0.5 - 1.0)	771	97.59	42.57	1040	77.38	57.43	1811	84.86
ALL	790	100.0	37.02	1344	100.0	62.98	2134	100.0

TABLE A12

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

SURGE TYPE 1

SRGMAX

	N	PCTN	MEAN	MAX	MIN
DURATION					
1	1125	32.66	0.62	2.06	0.51
2 OR MORE	2320	67.34	1.15	7.47	0.51
ALL	3445	100.0	0.97	7.47	0.51

SURGE TYPE 2

SRGMAX

	N	PCTN	MEAN	MAX	MIN
DURATION					
1	790	37.02	-0.58	-0.51	-2.42
2 OR MORE	1344	62.98	-0.86	-0.51	-4.39
ALL	2134	100.0	-0.76	-0.51	-4.39

ALL

SRGMAX

	N	PCTN	MEAN	MAX	MIN
DURATION					
1	1915	34.33	0.12	2.06	-2.42
2 OR MORE	3664	65.67	0.41	7.47	-4.39
ALL	5579	100.0	0.31	7.47	-4.39

TABLE A13

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

----- SRGTYP=1 -----

UNIVARIATE PROCEDURE

Variable=SRGMAX

	Histogram	#	Boxplot
7.25+*		1	*
.*		4	*
.*		3	*
.*		3	*
.*		6	*
.*		4	*
.*		16	*
.*		22	*
.*		45	*
.**		65	0
.**		88	0
.****		227	0
.*****		593	+-----+
0.75+*****		2761	*--+-*
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----			
* may represent up to 58 counts			

Variable=DUR

	Histogram	#	Boxplot
115+*		2	*
.			
.*		2	*
.*		2	*
.*		1	*
.*		5	*
.*		13	*
.*		38	*
.**		109	0
.*****		359	0
5+*****		3307	+--+-+
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----			
* may represent up to 69 counts			

TABLE A14

STATISTICS FOR SURGES AT FORT ERIE (1966 - 1987)
Based on monthly medians +/- 0.5 feet

----- SRTYP=2 -----

Variable=SRGMAX

	Histogram	#	Boxplot
-0.5+	*****	1057	+-----+
	*****	736	*--+-*
	*****	239	
	*****	138	0
	****	72	0
	**	37	0
	**	40	*
	*	14	*
	*	10	*
	*	9	*
	*	8	*
	*	1	*
	*	2	*
	*	3	*
	*	2	*
	*	1	*
	.		
	.		
	*	1	*
-4.3+		1	*

-----+-----+-----+-----+-----+-----+-----+-----+-----+
* may represent up to 23 counts

Variable=DUR

	Histogram	#	Boxplot
67.5+		1	*
.			
.			
*		4	*
*		1	*
*		6	*
*		7	*
*		13	*
*		21	*
**		41	0
**		45	0
****		133	0
*****		474	+-----+
*****		1625	*--+-*

-----+-----+-----+-----+-----+-----+-----+-----+-----+
* may represent up to 34 counts

APPENDIX 2

This Appendix presents the results of the statistical analysis of the wind speed surges. As explained in Section 2.2, wind speeds larger than the monthly median plus 8 km/h are called type 1 surges, and elevation levels smaller than the monthly median minus 8 km/h are called type 2 surges. The following statistics are given in Tables B.1 to Table B.14.

- The number of surge events in a month for each year: Tables B1 and B2.
- The proportion of surges in a month by duration of the surge (1 hour, 2 hours, ... and 7 or more hours), together with the maximum, minimum, mean and standard deviation of the surge intensity: Tables B3 to B10.
- The distribution of the number of surges by range intensity (in increments of 15 cm (0.5 ft)): Tables B11 and B12.
- Histograms of the distribution of the duration and intensity of the surges: Tables B13 and B14.

TABLE B1

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

surge type 1

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	NOV	DEC	ALL
	N	N	N	N	N	N	N	N	N	N	N	N
YEAR												
1966	20	18	26	30	13	7	12	21	35	39	24	245
1967	119	40	46	39	36	17	6	24	20	144	33	524
1968	53	117	40	42	46	23	17	25	17	38	51	469
1969	16	11	15	20	9	1	6	1	2	7	9	97
1970	4	2	18	16	9	8	0	0	2	4	21	84
1971	10	11	5	5	9	5	2	4	1	6	11	69
1972	4	6	13	16	9	5	0	9	1	10	11	84
1973	7	0	3	7	2	1	0	0	1	8	1	30
1974	6	6	4	10	2	0	3	0	1	6	6	44
1975	2	1	5	6	3	0	2	0	7	3	3	32
1976	3	1	8	11	2	1	1	1	0	0	0	28
1977	1	5	5	9	10	1	0	0	4	7	6	48
1978	38	27	43	43	41	15	29	23	37	47	26	369
1979	39	36	38	38	40	19	16	21	18	28	49	342
ALL	322	281	269	292	231	103	94	129	146	347	251	2465

TABLE B2

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

surge type 2

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	NOV	DEC	ALL
	N	N	N	N	N	N	N	N	N	N	N	N
YEAR												
1966	18	1	11	3	12	2	0	106	96	131	142	522
1967	125	140	90	110	106	101	83	82	78	118	150	1183
1968	110	127	124	115	102	100	109	105	74	129	132	1227
1969	90	38	44	45	52	25	13	7	27	17	31	389
1970	0	0	1	1	2	0	0	0	0	2	0	6
1971	1	4	1	0	0	0	0	0	0	0	0	6
1972	0	0	0	0	1	0	0	0	0	0	0	1
1975	0	0	0	0	1	0	0	0	0	0	0	1
1978	156	104	128	109	84	116	98	80	96	116	156	1243
1979	138	109	136	118	98	107	75	98	82	118	97	1176
ALL	638	523	535	501	458	451	378	478	453	631	708	5754

TABLE B3

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians $\pm$ 8 km/hr

DURATION 1
AND SURGE TYPE 1

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	204	13.65	9.00	10.61	23.00	1.97
FEB	197	13.18	9.00	10.57	20.00	2.02
MAR	156	10.43	9.00	10.30	18.00	1.80
APR	138	9.23	9.00	10.30	23.00	2.32
MAY	120	8.03	9.00	10.93	22.00	2.20
JUN	64	4.28	9.00	10.48	19.00	2.30
JUL	59	3.95	9.00	10.17	15.00	1.51
AUG	85	5.69	9.00	10.53	25.00	2.20
SEP	82	5.48	9.00	10.68	22.00	2.34
NOV	247	16.52	9.00	10.25	17.00	1.52
DEC	143	9.57	9.00	10.44	21.00	2.14
ALL	1495	100.0	9.00	10.47	25.00	2.00

TABLE B4

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

DURATION 1
AND SURGE TYPE 2

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	144	9.34	-34.0	-11.4	-9.00	3.70
FEB	105	6.81	-23.0	-12.1	-9.00	3.41
MAR	140	9.09	-26.0	-11.4	-9.00	3.47
APR	132	8.57	-27.0	-12.3	-9.00	3.72
MAY	172	11.16	-22.0	-12.0	-9.00	3.48
JUN	139	9.02	-33.0	-12.1	-9.00	3.99
JUL	138	8.96	-23.0	-12.0	-9.00	3.34
AUG	182	11.81	-31.0	-11.9	-9.00	3.33
SEP	151	9.80	-24.0	-11.5	-9.00	3.00
NOV	138	8.96	-40.0	-12.5	-9.00	4.65
DEC	100	6.49	-34.0	-12.0	-9.00	4.36
ALL	1541	100.0	-40.0	-11.9	-9.00	3.68

TABLE B5

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

DURATION 2
AND SURGE TYPE 1

		SRGMAX				
	N	PCTN	MIN	MEAN	MAX	STD
JAN	81	11.28	9.00	15.20	30.00	4.33
FEB	62	8.64	9.00	12.58	20.00	2.92
MAR	83	11.56	9.00	14.30	24.00	4.32
APR	110	15.32	9.00	14.22	28.00	4.34
MAY	92	12.81	9.00	14.42	27.00	3.63
JUN	24	3.34	9.00	12.21	16.00	1.93
JUL	32	4.46	9.00	13.06	19.00	2.70
AUG	40	5.57	9.00	13.05	24.00	3.25
SEP	50	6.96	9.00	14.16	21.00	3.54
NOV	73	10.17	9.00	14.89	30.00	4.62
DEC	71	9.89	9.00	12.89	22.00	2.97
ALL	718	100.0	9.00	13.97	30.00	3.89

TABLE B6

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

DURATION 2
AND SURGE TYPE 2

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	494	11.73	-55.0	-20.8	-9.00	8.15
FEB	418	9.92	-88.0	-21.4	-9.00	8.05
MAR	395	9.38	-49.0	-21.2	-9.00	7.66
APR	369	8.76	-46.0	-22.6	-9.00	8.53
MAY	286	6.79	-48.0	-19.9	-9.00	7.34
JUN	312	7.41	-36.0	-18.7	-9.00	5.54
JUL	240	5.70	-32.0	-17.6	-9.00	5.11
AUG	296	7.03	-43.0	-18.0	-9.00	5.34
SEP	302	7.17	-41.0	-17.9	-9.00	6.41
NOV	493	11.70	-52.0	-20.5	-9.00	6.97
DEC	608	14.43	-50.0	-21.6	-9.00	7.25
ALL	4213	100.0	-88.0	-20.3	-9.00	7.34

TABLE B7

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)

Based on monthly medians +/- 8 km/hr

DURATION 3
AND SURGE TYPE 1

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	2	5.41	11.00	13.50	16.00	3.54
FEB	3	8.11	9.00	11.67	15.00	3.06
MAR	6	16.22	10.00	12.00	14.00	1.67
APR	4	10.81	9.00	11.25	13.00	2.06
MAY	1	2.70	11.00	11.00	11.00	0
JUN	6	16.22	10.00	12.17	14.00	1.83
JUL	1	2.70	14.00	14.00	14.00	0
AUG	1	2.70	14.00	14.00	14.00	0
SEP	4	10.81	9.00	15.50	21.00	5.51
NOV	3	8.11	10.00	13.33	18.00	4.16
DEC	6	16.22	10.00	12.00	17.00	2.90
ALL	37	100.0	9.00	12.57	21.00	2.89

TABLE B8

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

DURATION 4
AND SURGE TYPE 1

			SRGMAX			
	N	PCTN	MIN	MEAN	MAX	STD
JAN	8	22.86	10.00	15.88	24.00	6.10
FEB	2	5.71	13.00	15.00	17.00	2.83
MAR	3	8.57	13.00	15.33	18.00	2.52
APR	4	11.43	12.00	17.75	32.00	9.60
MAY	3	8.57	11.00	15.67	22.00	5.69
JUN	1	2.86	16.00	16.00	16.00	0
JUL	1	2.86	13.00	13.00	13.00	0
SEP	1	2.86	12.00	12.00	12.00	0
NOV	5	14.29	10.00	11.20	12.00	0.84
DEC	7	20.00	11.00	14.29	18.00	3.04
ALL	35	100.0	10.00	14.80	32.00	4.87

TABLE B9

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

DURATION 5
AND SURGE TYPE 1

SRGMAX						
	N	PCTN	MIN	MEAN	MAX	STD
JAN	4	7.55	12.00	18.50	27.00	6.35
FEB	5	9.43	11.00	17.00	26.00	5.66
MAR	7	13.21	17.00	19.43	23.00	2.82
APR	12	22.64	10.00	17.58	27.00	5.57
MAY	10	18.87	12.00	16.20	25.00	3.94
JUN	1	1.89	14.00	14.00	14.00	0
JUL	1	1.89	20.00	20.00	20.00	0
AUG	1	1.89	16.00	16.00	16.00	0
SEP	6	11.32	12.00	18.33	23.00	4.37
NOV	1	1.89	21.00	21.00	21.00	0
DEC	5	9.43	11.00	13.00	18.00	2.83
ALL	53	100.0	10.00	17.25	27.00	4.57

TABLE B10

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

DURATION 6
AND SURGE TYPE 1

			SRGMAX			
	N	PCTN	MIN	MEAN	MAX	STD
JAN	3	25.00	10.00	14.67	17.00	4.04
FEB	2	16.67	14.00	18.00	22.00	5.66
MAR	1	8.33	11.00	11.00	11.00	0
APR	3	25.00	11.00	15.33	19.00	4.04
NOV	2	16.67	10.00	12.50	15.00	3.54
DEC	1	8.33	17.00	17.00	17.00	0
ALL	12	100.0	10.00	14.92	22.00	3.82

TABLE B11

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

DURATION 7 or more
AND SURGE TYPE 1

	SRGMAX					
	N	PCTN	MIN	MEAN	MAX	STD
JAN	20	17.39	13.00	24.50	44.00	9.11
FEB	10	8.70	11.00	20.60	37.00	8.21
MAR	13	11.30	13.00	21.15	36.00	7.51
APR	21	18.26	11.00	18.90	31.00	6.50
MAY	5	4.35	10.00	24.80	35.00	9.12
JUN	7	6.09	11.00	23.14	37.00	7.86
AUG	2	1.74	13.00	17.00	21.00	5.66
SEP	3	2.61	21.00	22.67	25.00	2.08
NOV	16	13.91	11.00	21.00	34.00	7.08
DEC	18	15.65	13.00	20.50	30.00	6.08
ALL	115	100.0	10.00	21.40	44.00	7.43

TABLE B12

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

SURGE TYPE 1

SRGMAX RANGE	DURATION							
	1			2 or more			ALL	
	N	COL PCT	ROW PCT	N	COL PCT	ROW PCT	N	PCTN
8.0 - 10.0	615	41.14	91.52	57	5.88	8.48	672	27.26
10.0 - 12.0	575	38.46	72.33	220	22.68	27.67	795	32.25
12.0 - 14.0	203	13.58	53.99	173	17.84	46.01	376	15.25
14.0 - 16.0	57	3.81	24.68	174	17.94	75.32	231	9.37
16.0 - 18.0	25	1.67	19.08	106	10.93	80.92	131	5.31
18.0 - 20.0	11	0.74	11.00	89	9.18	89.00	100	4.06
20.0 - 22.0	4	0.27	7.84	47	4.85	92.16	51	2.07
22.0 - 24.0	4	0.27	11.43	31	3.20	88.57	35	1.42
24.0 - 26.0	1	0.07	3.57	27	2.78	96.43	28	1.14
26.0 - 28.0	0	0	0	20	2.06	100.0	20	0.81
28.0 - 30.0	0	0	0	9	0.93	100.0	9	0.37
above 30.0	0	0	0	17	1.75	100.0	17	0.69
ALL	1495	100.0	60.65	970	100.0	39.35	2465	100.0

TABLE 13

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

SURGE TYPE 2

	DURATION							
	1			2 or more			ALL	
	N	COL PCT	ROW PCT	N	COL PCT	ROW PCT	N	PCTN
SRGMAX RANGE								
(above 30.0)	6	0.39	1.22	485	11.51	98.78	491	8.53
(28.0 - 30.0)	1	0.06	0.47	214	5.08	99.53	215	3.74
(26.0 - 28.0)	6	0.39	2.39	245	5.82	97.61	251	4.36
(24.0 - 26.0)	11	0.71	3.11	343	8.14	96.89	354	6.15
(22.0 - 24.0)	21	1.36	5.32	374	8.88	94.68	395	6.86
(20.0 - 22.0)	23	1.49	5.57	390	9.26	94.43	413	7.18
(18.0 - 20.0)	58	3.76	10.74	482	11.44	89.26	540	9.38
(16.0 - 18.0)	91	5.91	16.73	453	10.75	83.27	544	9.45
(14.0 - 16.0)	133	8.63	24.27	415	9.85	75.73	548	9.52
(12.0 - 14.0)	230	14.93	34.90	429	10.18	65.10	659	11.45
(10.0 - 12.0)	529	34.33	62.38	319	7.57	37.62	848	14.74
(8.0 - 10.0)	432	28.03	87.10	64	1.52	12.90	496	8.62
ALL	1541	100.0	26.78	4213	100.0	73.22	5754	100.0

TABLE B14

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

SURGE TYPE 1

	SRGMAX				
	N	PCTN	MEAN	MAX	MIN
DURATION					
1	1495	60.65	10.47	25.00	9.00
2 or more	970	39.35	15.02	44.00	9.00
ALL	2465	100.0	12.26	44.00	9.00

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

SURGE TYPE 2

	SRGMAX				
	N	PCTN	MEAN	MAX	MIN
DURATION					
1	1541	26.78	-11.9	-9.00	-40.0
2 or more	4213	73.22	-20.3	-9.00	-88.0
ALL	5754	100.0	-18.1	-9.00	-88.0

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

ALL

	SRGMAX				
	N	PCTN	MEAN	MAX	MIN
DURATION					
1	3036	36.94	-0.89	25.00	-40.0
2 or more	5183	63.06	-13.7	44.00	-88.0
ALL	8219	100.0	-8.98	44.00	-88.0

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

UNIVARIATE PROCEDURE

	Histogram	#	Boxplot
45+*	.	1	*
. *	.	1	*
. *	.	3	*
. *	.	3	*
. *	.	3	*
. *	.	6	*
. *	.	9	*
27+***	.	21	*
. **	.	29	0
. ***	.	38	0
. ***	.	54	0
. *****	.	106	
. *****	.	137	
. *****	.	252	
. *****	.	412	+ - + - + - +
. *****	.	864	* - - - - *
9+*****	.	738	+ - - - - +
- - - + - - - + - - - + - - - + - - - + - - - + - - - + - - -			

* may represent up to 18 counts

[illegible]

STATISTICS FOR SURGES IN AVERAGE WIND SPEED (1966 - 1979)
Based on monthly medians +/- 8 km/hr

UNIVARIATE PROCEDURE

	Histogram	#	Boxplot
-7.5+*****		1103	
.*****		1748	+-----+
.*****		1430	*-+--+*
.*****		1062	+-----+
.*****		604	
.*****		283	
.***		76	0
.**		41	0
-47.5+*		12	0
.*		2	0
.			
.			
.			
.			
.			
-87.5+*		1	*
-----+-----+-----+-----+-----+-----+-----+-----+-----+-----			
* may represent up to 37 counts			

```

Histogram                                     #      Boxplot
2.025+*****                               4635 +-----+
      |
1.925+
      |
      |
1.825+
      |
      |
1.725+
      |   +
      |
1.625+
      |
      |
1.525+
      |
      |
1.425+
      |
      |
1.325+
      |
      |
1.225+
      |
      |
1.125+
      |
      |
1.025+*****                               1727 +-----+
      |
      +-----+-----+-----+-----+-----+-----+-----+

```

* may represent up to 97 counts

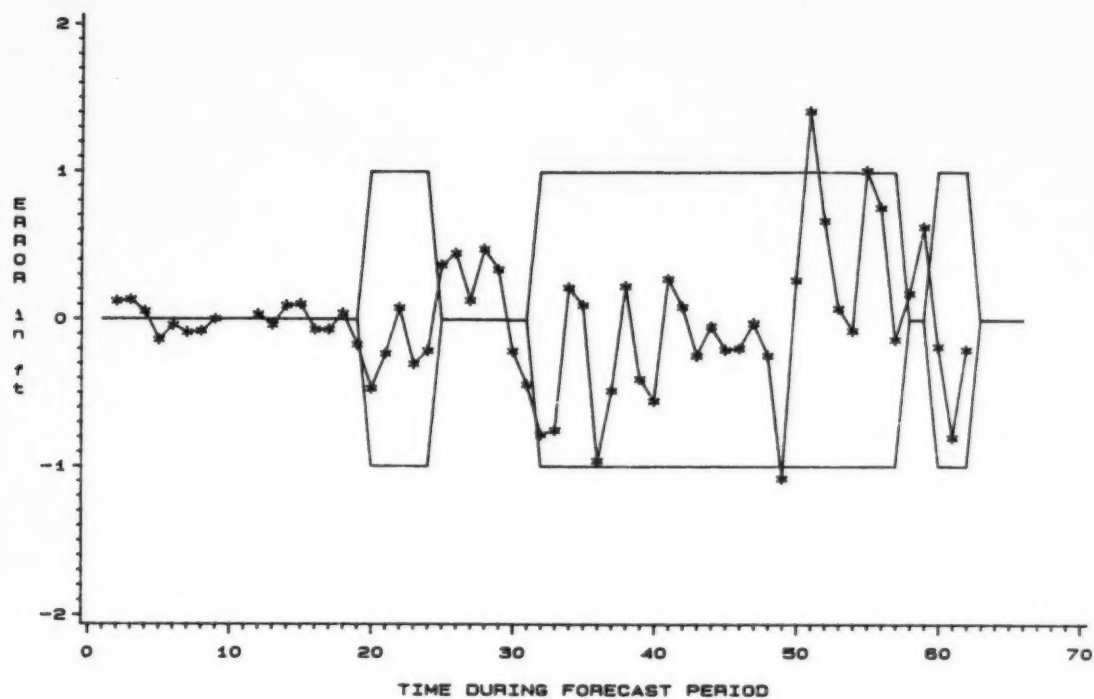
APPENDIX 3

This Appendix presents plots of the 2-step and 4-step ahead forecast errors obtained using a multivariate nonparametric model for each one of the forecast periods used in the study.

The memory of the nonparametric model is ($ds=5$, $dw=3$). Each plot includes a ± 30 cm (1 ft) (for 2-step ahead) or a ± 60 cm (2 ft) (for 4-step ahead) reference lines for those hours associated with surge events.

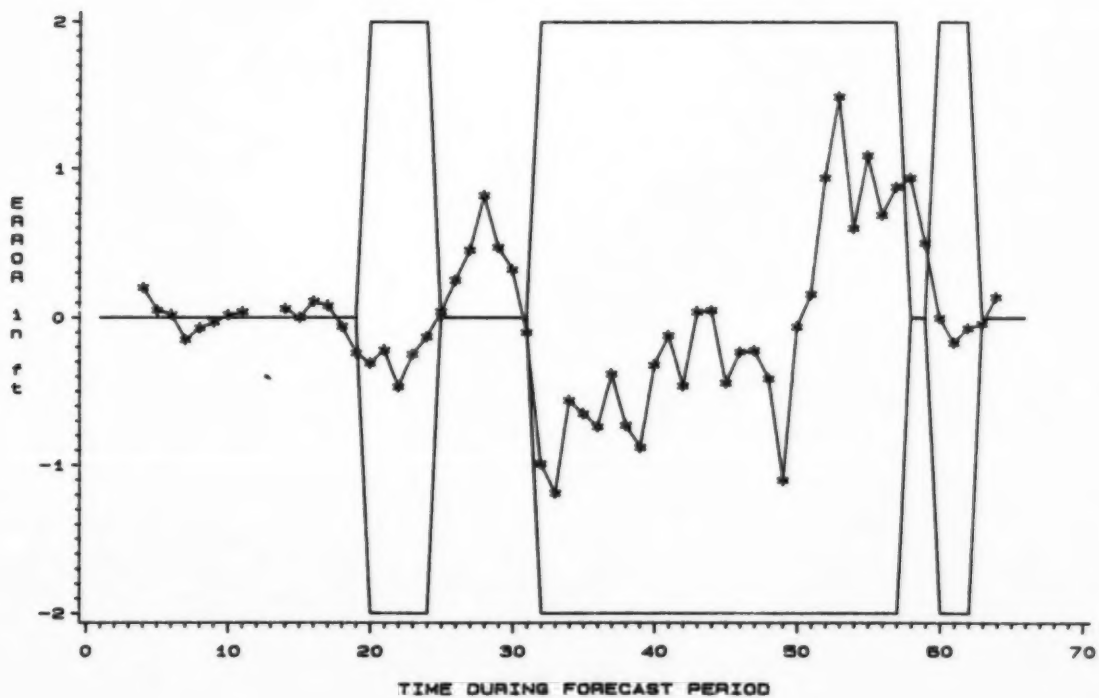
FORECAST ERRORS

DATE-17 APR 1969 2-Step ahead



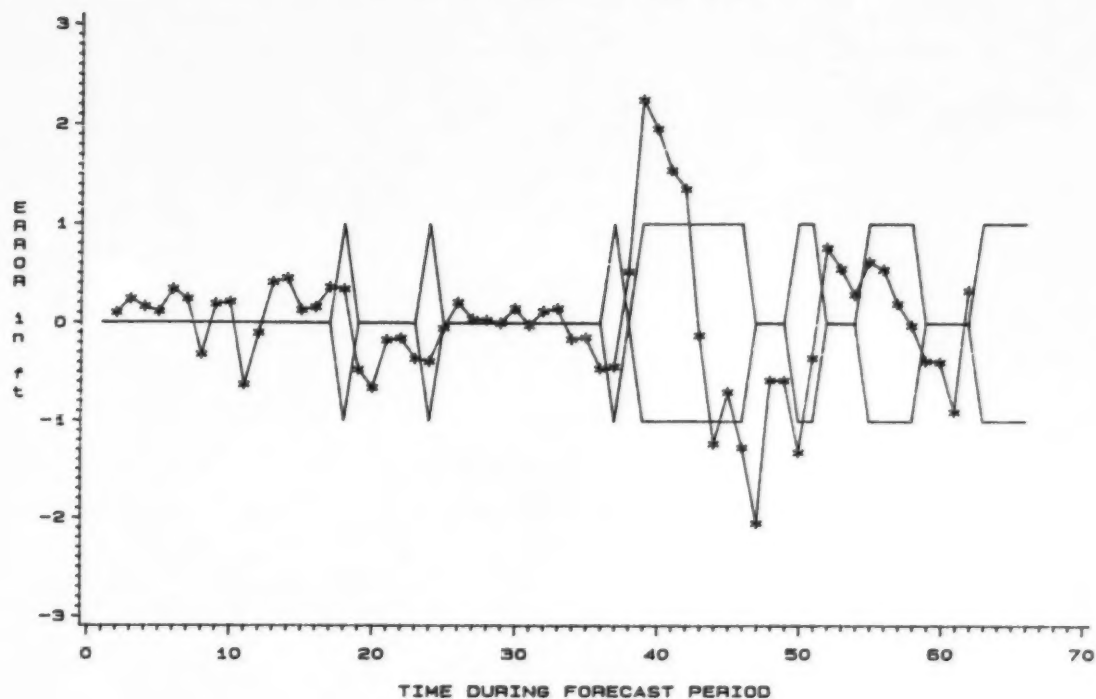
FORECAST ERRORS

DATE-17 APR 1969 4-Step ahead



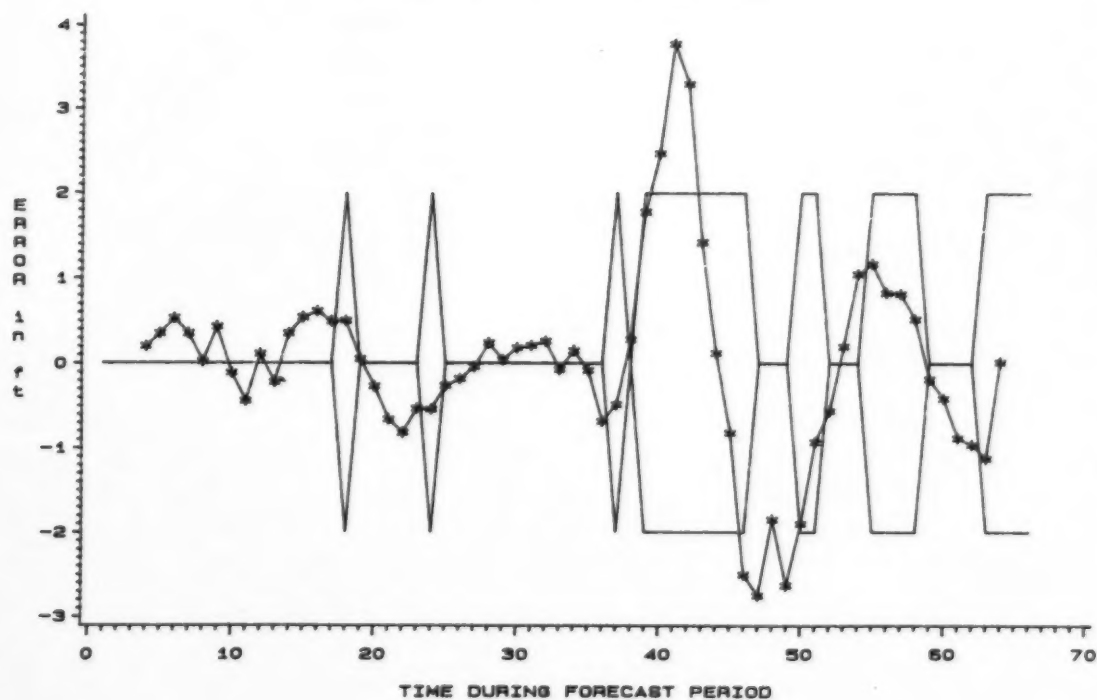
FORECAST ERRORS

DATE-8 MAY 1969 2-Step ahead



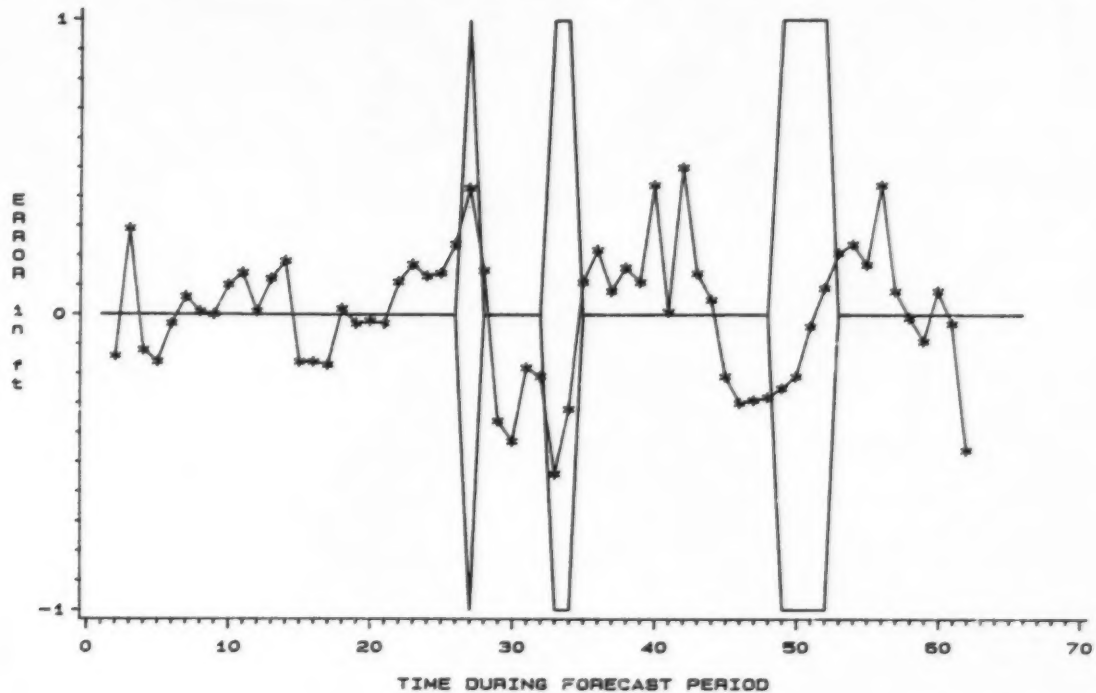
FORECAST ERRORS

DATE-8 MAY 1969 4-Step ahead



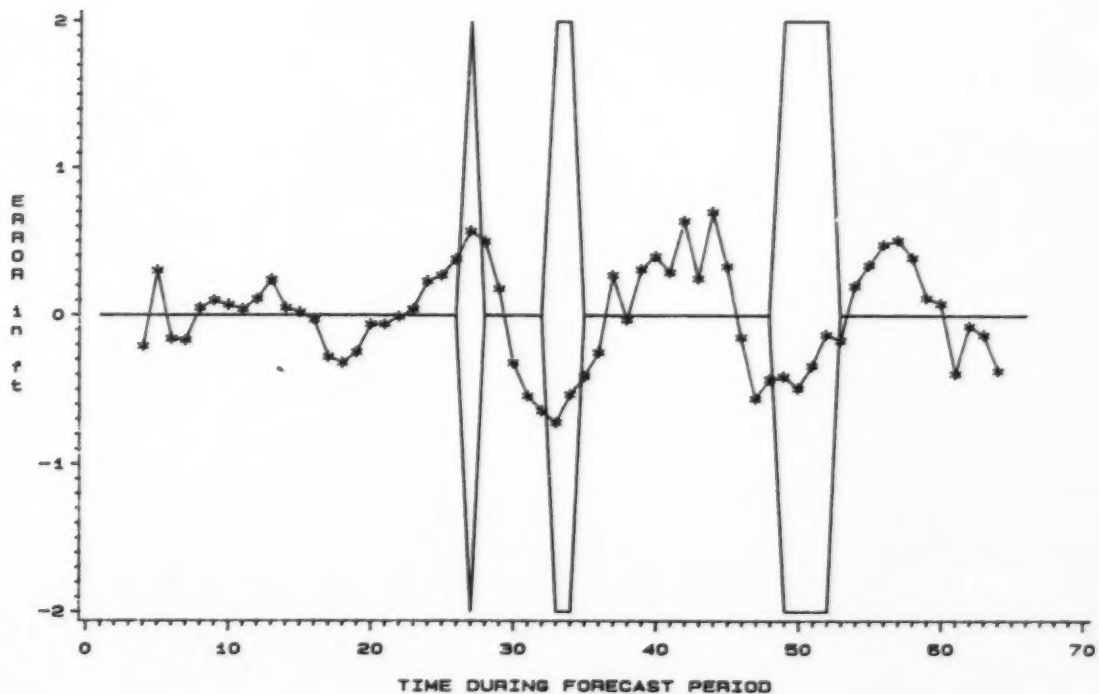
FORECAST ERRORS

DATE-23 SEP 1989 2-Step ahead



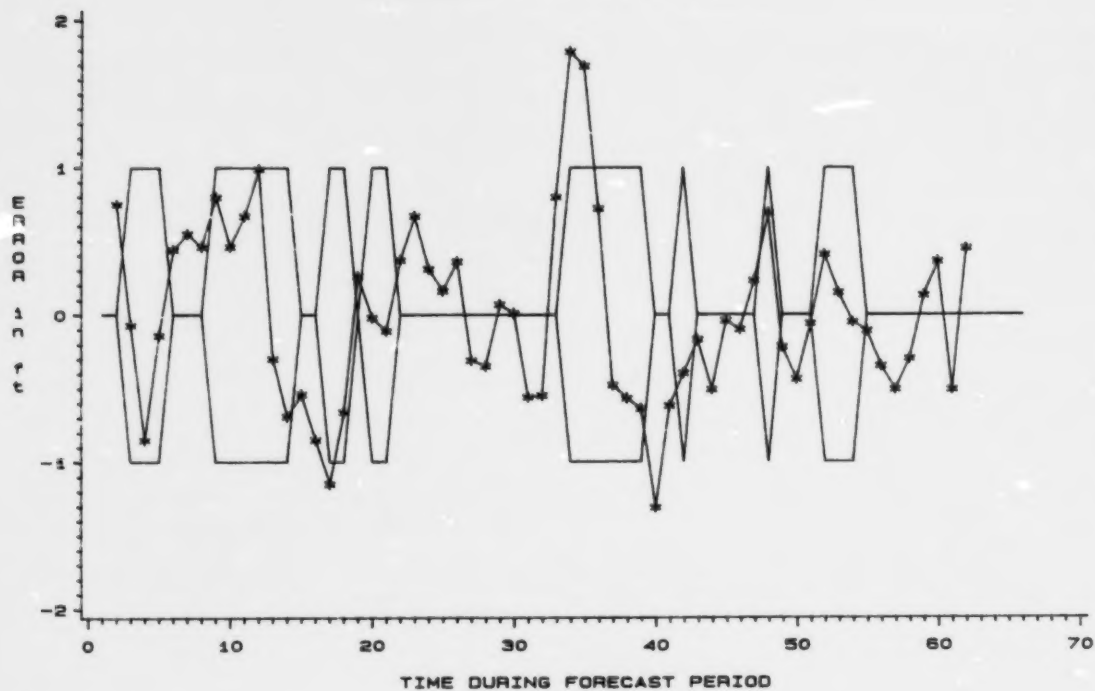
FORECAST ERRORS

DATE-23 SEP 1989 4-Step ahead



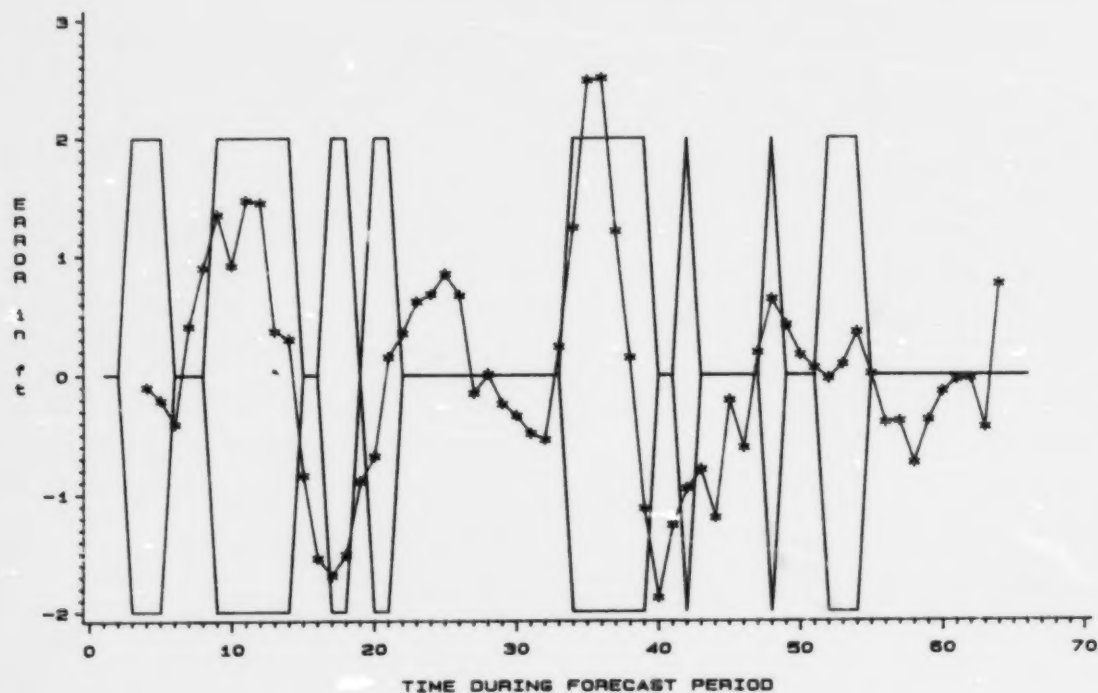
FORECAST ERRORS

DATE-20 APR 1970 2-Step ahead



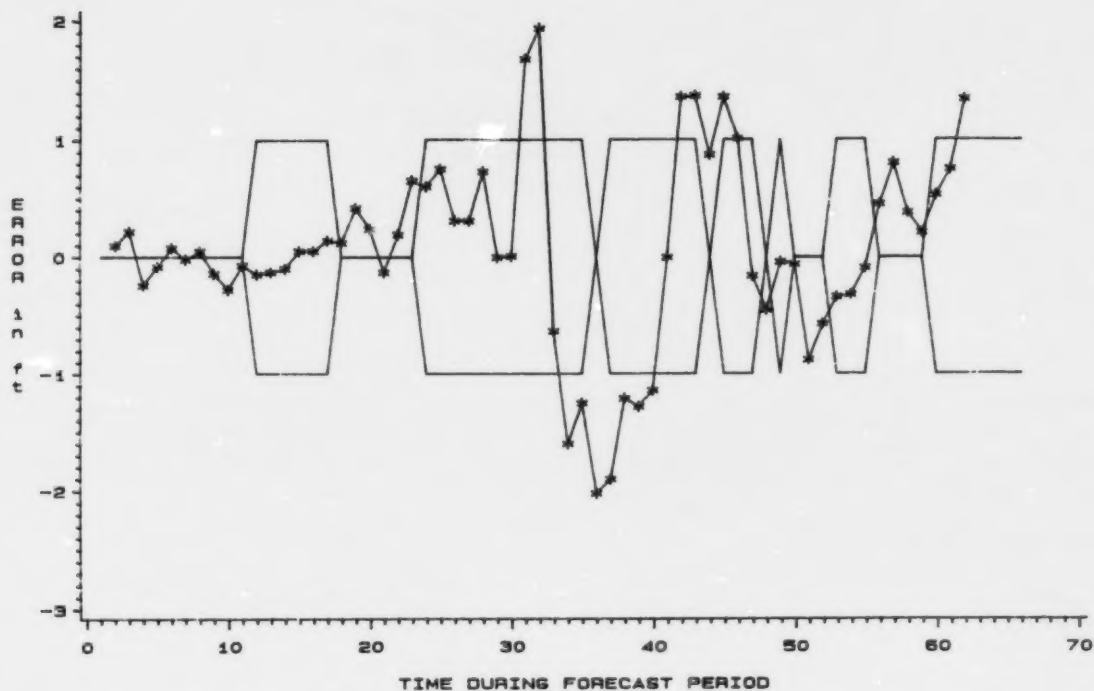
FORECAST ERRORS

DATE-20 APR 1970 4-Step ahead



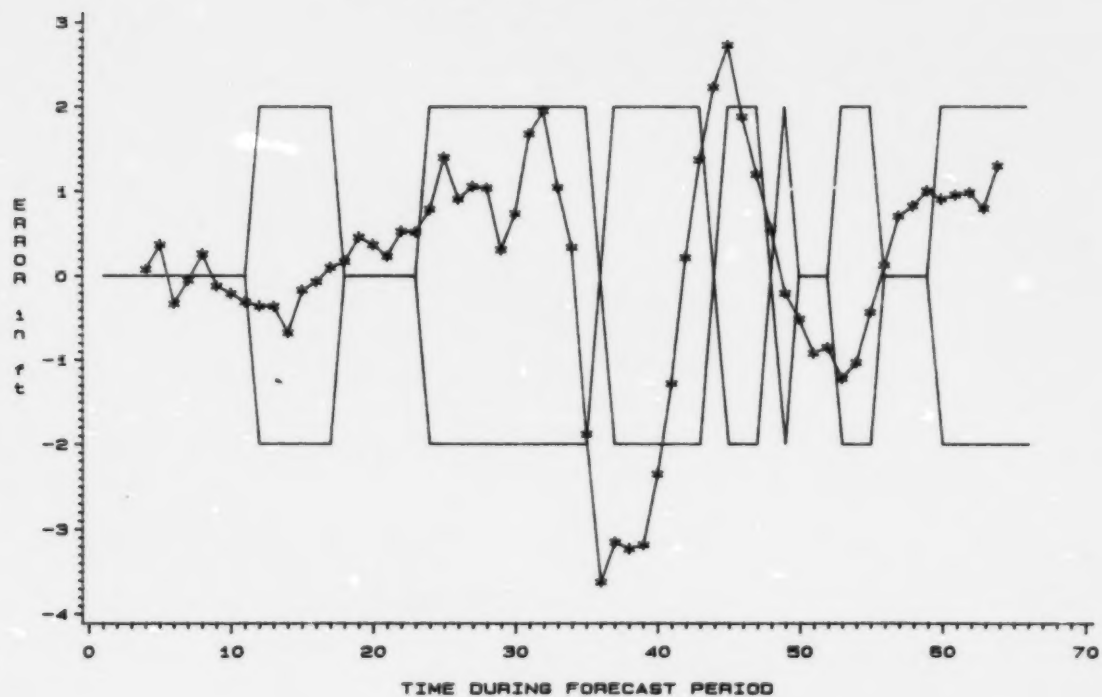
FORECAST ERRORS

DATE-3 DEC 1970 2-Step ahead



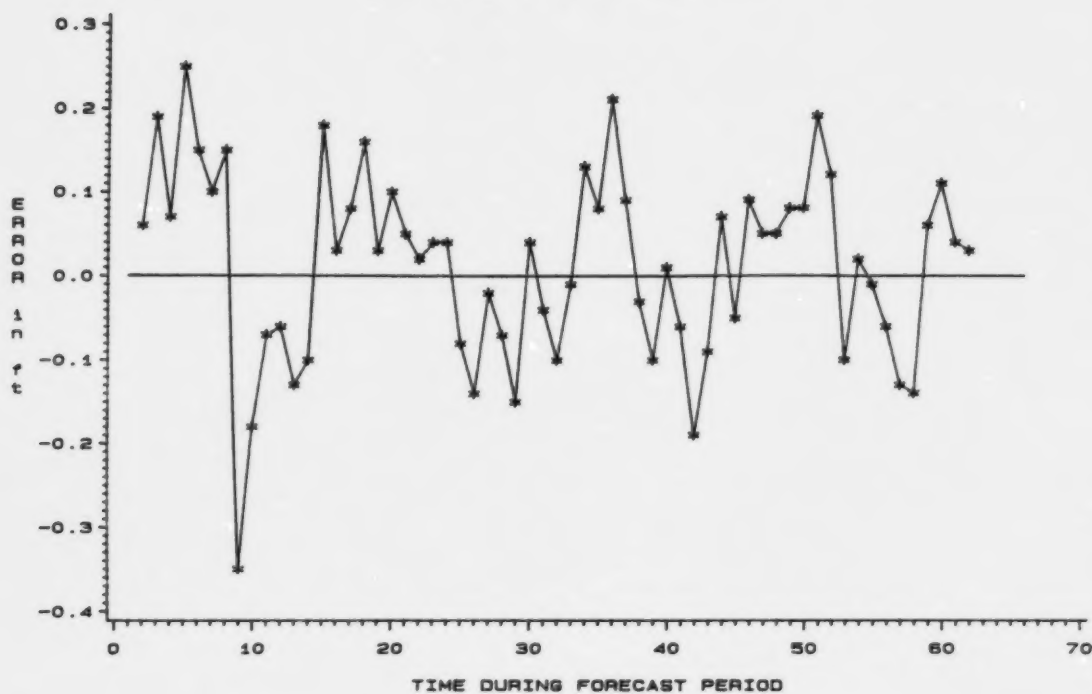
FORECAST ERRORS

DATE-3 DEC 1970 4-Step ahead



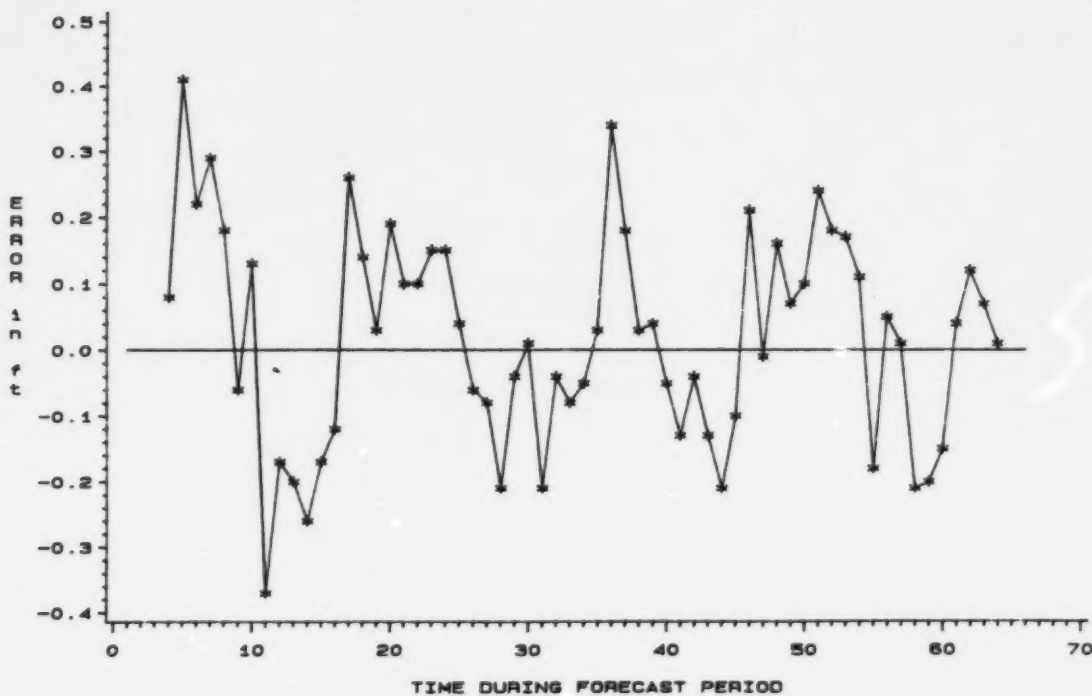
FORECAST ERRORS

DATE-19 OCT 1971 2-Step ahead



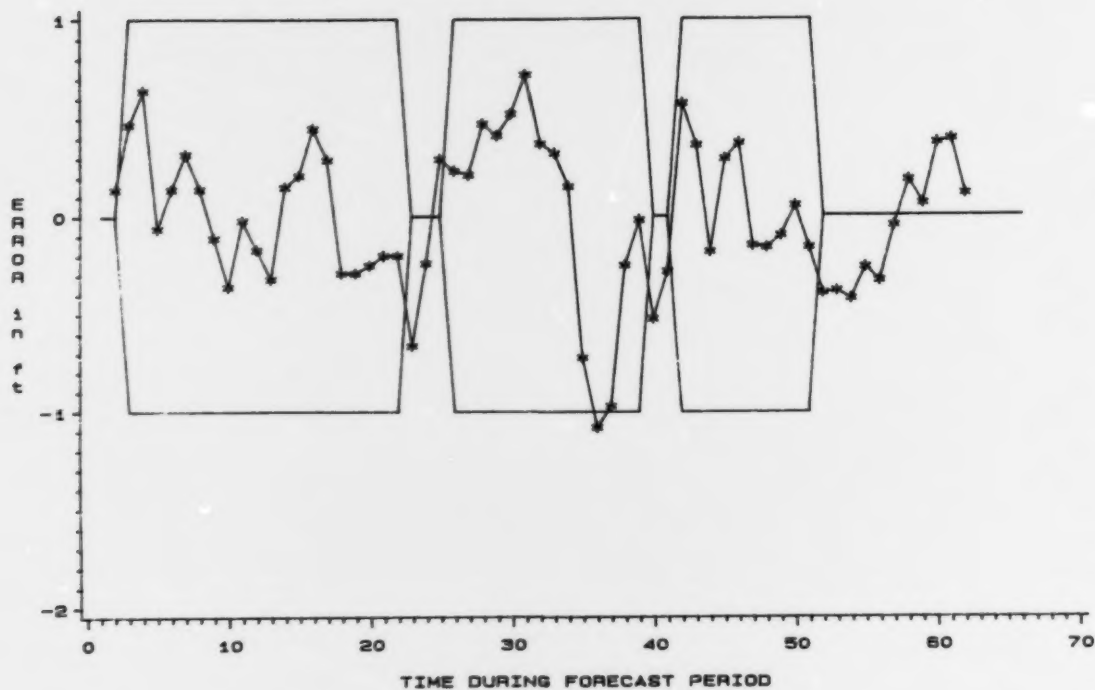
FORECAST ERRORS

DATE-19 OCT 1971 4-Step ahead



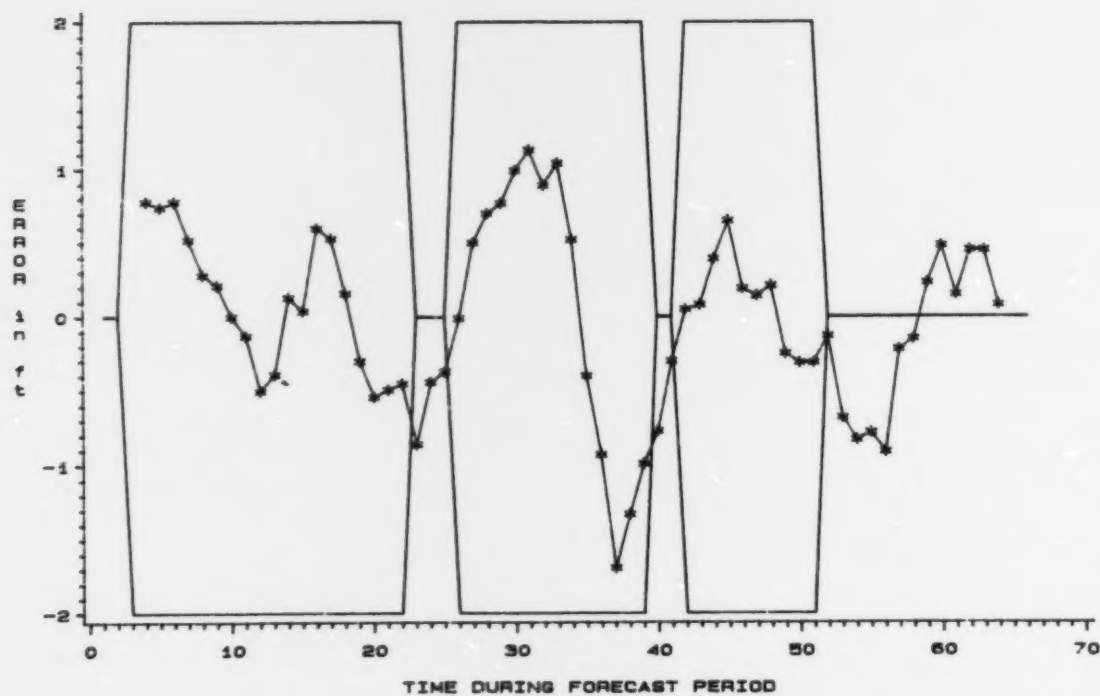
FORECAST ERRORS

DATE-6 NOV 1971 2-Step ahead

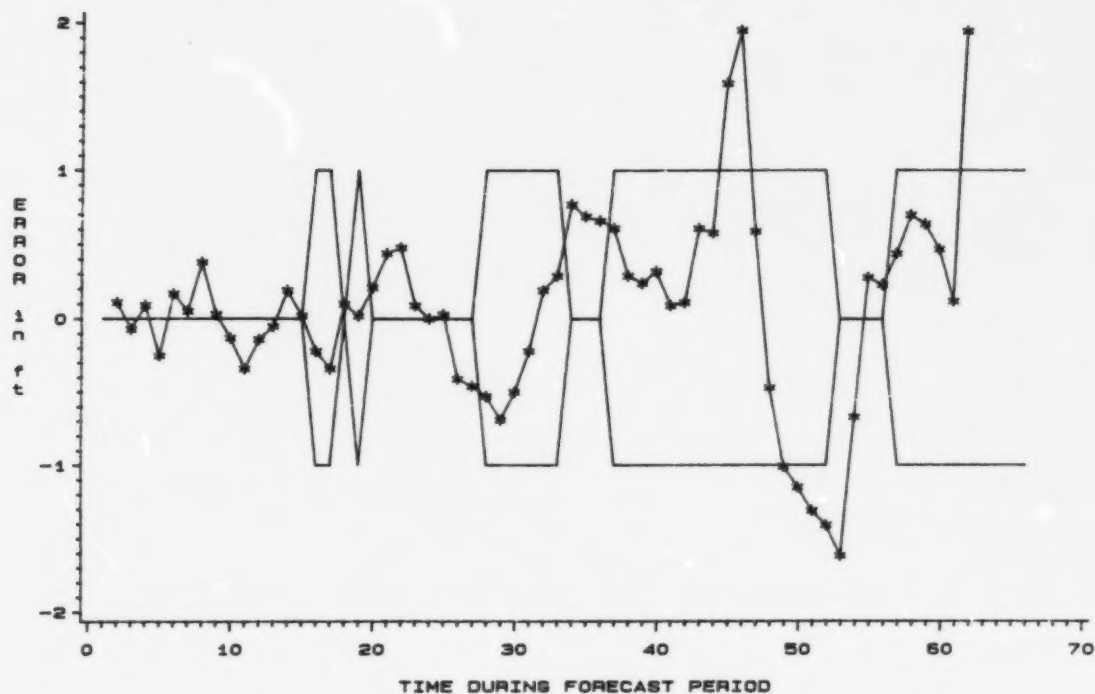


FORECAST ERRORS

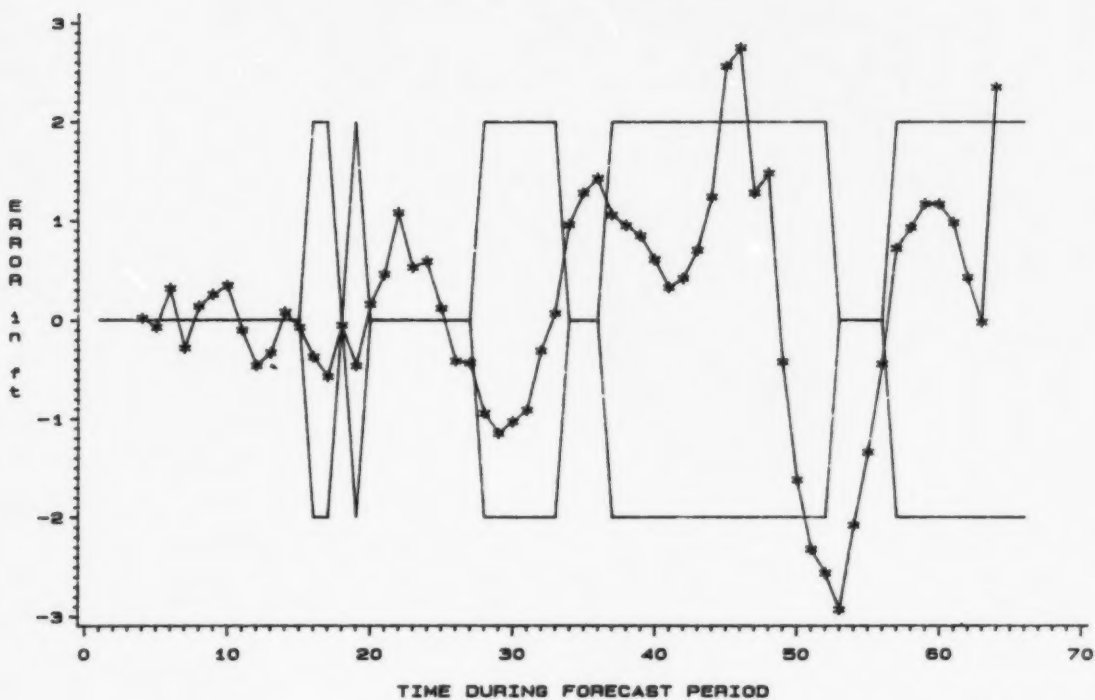
DATE-6 NOV 1971 4-Step ahead



FORECAST ERRORS DATE-14 DEC 1971 2-Step ahead

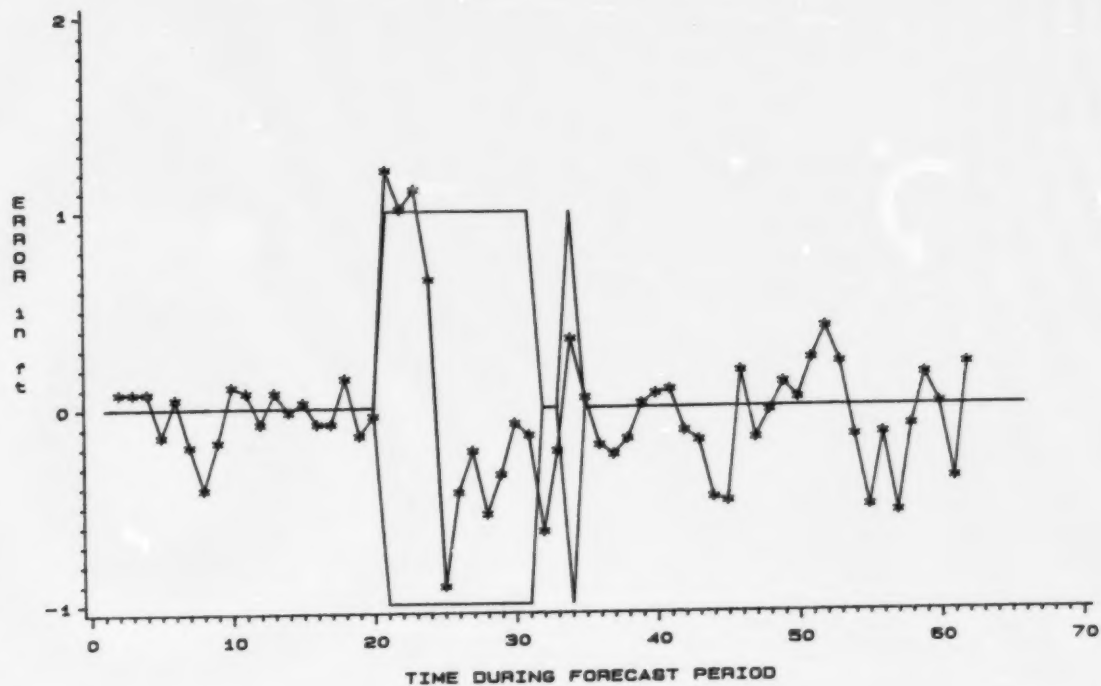


FORECAST ERRORS DATE-14 DEC 1971 4-Step ahead



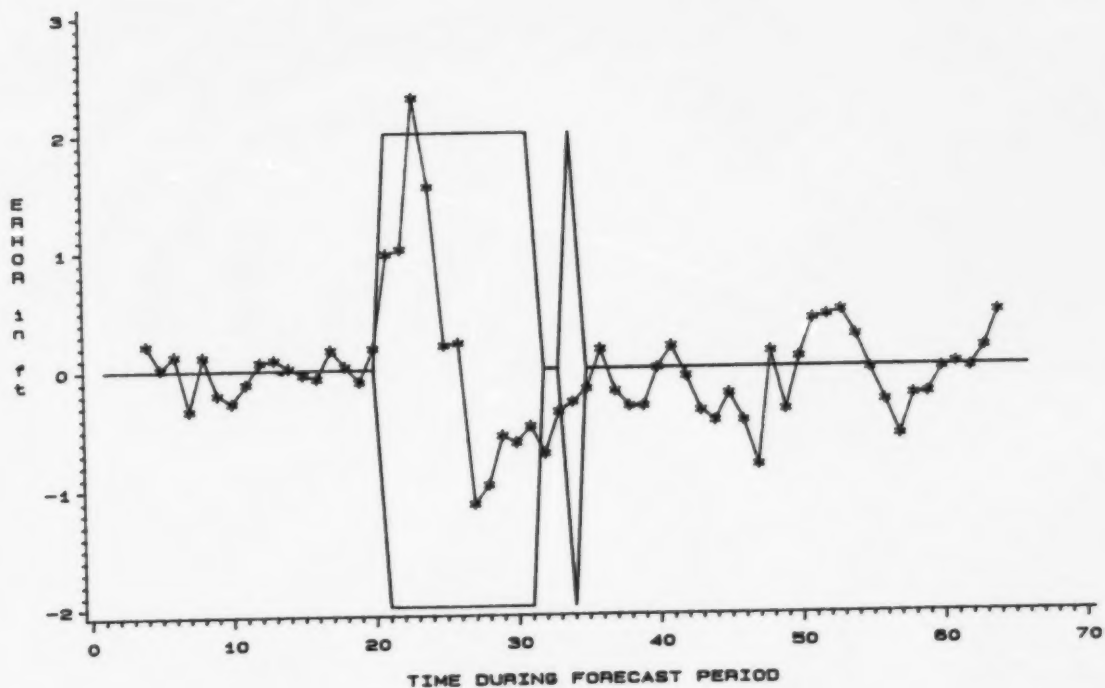
FORECAST ERRORS

DATE-10 JUN 1979 2-Step ahead



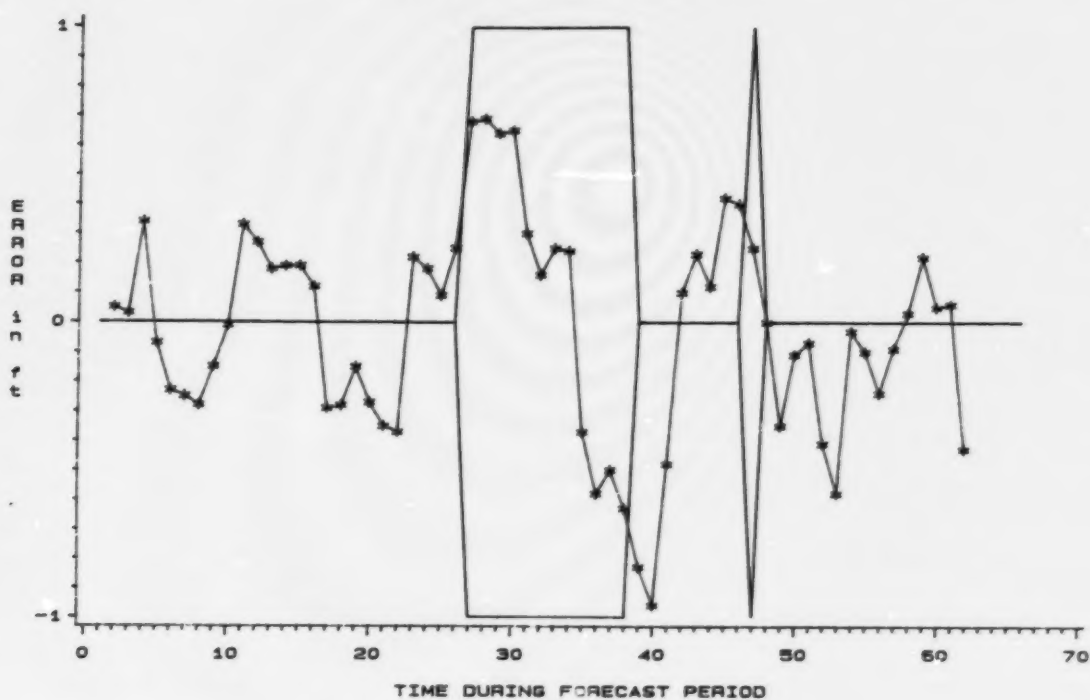
FORECAST ERRORS

DATE-10 JUN 1979 4-Step ahead



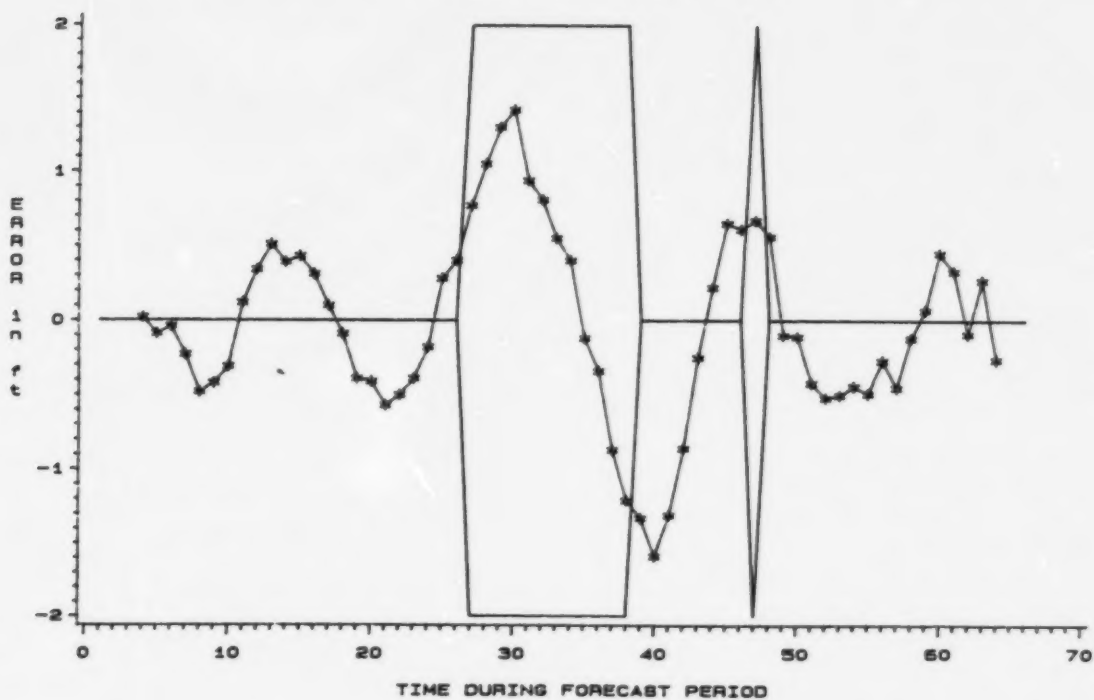
FORECAST ERRORS

DATE-9 AUG 1979 2-Step ahead



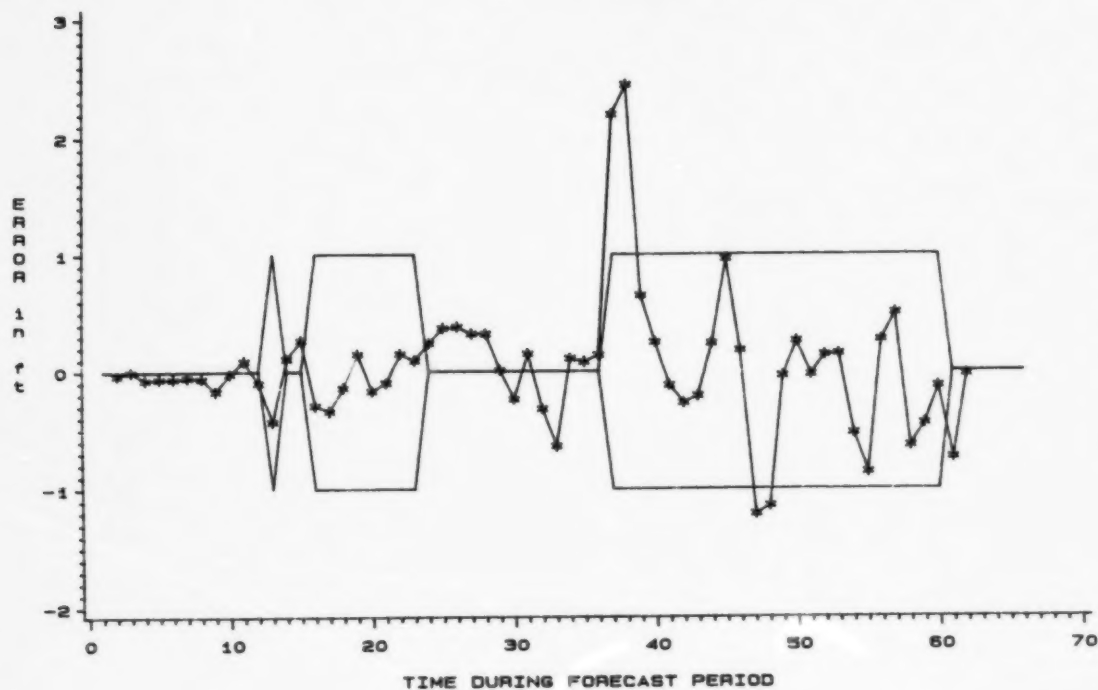
FORECAST ERRORS

DATE-9 AUG 1979 4-Step ahead



FORECAST ERRORS

DATE-25 NOV 1979 2-Step ahead



FORECAST ERRORS

DATE-25 NOV 1979 4-Step ahead

